U.S. Department of the Interior
U.S. Geological Survey

Evidence for Hot Mississippi Valley–Type Brines in the Reelfoot Rift Complex, South-Central United States, in Late Pennsylvanian–Early Permian

U.S. Geological Survey Professional Paper 1577

science for a changing world

Evidence for Hot Mississippi Valley–Type Brines in the Reelfoot Rift Complex, South-Central United States, in Late Pennsylvanian–Early Permian

By D.L. Leach, L.E. Apodaca, J.E. Repetski, J.W. Powell, *and* E.L. Rowan

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1577

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1997

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Mark Schaefer, Acting Director

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Evidence for hot Mississippi Valley–type brines in the Reelfoot rift complex, south-central United States, in Late Pennsylvanian–Early Permian / by D.L. Leach . . . [et al.].
p. cm. (U.S. Geological Survey professional paper ; 1577)
Includes bibliographical references (p.).
Supt of Docs. No.: I 19.16:1755
1. Hydrothermal alteration—Missouri—New Madrid Region. 2. Geology, Stratigraphic—Pennsylvanian. 3. Geology, Stratigraphic—Permian. 4. Geology—Missouri—New Madrid Region.
I. Leach, D.L. II. Series.
QE390.5.E85
551.230976—dc21 97-12553
cip

CONTENTS

FIGURES

Evidence for Hot Mississippi Valley–Type Brines in the Reelfoot Rift Complex, South-Central United States, in Late Pennsylvanian–Early Permian

By D.L. Leach, L.E. Apodaca, J.E. Repetski, J.W. Powell, *and* E.L. Rowan

ABSTRACT

Petrographic and fluid inclusion studies of sparry dolomite cement from Upper Cambrian to Lower Ordovician rocks and conodont thermal-alteration indices provide evidence that hot Mississippi Valley–type brines were once present in the Reelfoot rift complex. The cathodoluminescent microstratigraphy of sparry dolomite cement in the Reelfoot rift resembles that of sparry dolomite cement associated with widespread Mississippi Valley–type mineral deposition in the Ozark region. If correlative cathodoluminescent zones in the sparry dolomite from the Ozark and Reelfoot rift regions indicate broadly contemporaneous dolomite deposition, then the results show that the Ozark Mississippi Valley–type hydrothermal system extended into the Reelfoot region and onto the western flank of the Nashville dome. Independent evidence supports the migration of Mississippi Valley–type brines into the Ozark region from the Reelfoot rift complex in late Paleozoic time.

Values for conodont thermal-alteration indices found in the Dow Chemical #1 Wilson drill hole in the Reelfoot rift complex provide evidence for the amount of post-Early Ordovician strata that eroded before the Cretaceous. For a burial thermal gradient of 30°C/km, about 2.1–3.7 kilometers of strata have been removed at the location of the Dow Chemical #1 Wilson drill hole. The total thickness of post-Lamotte Sandstone strata present before pre-Cretaceous erosion could have been between 5.3 and 6.3 kilometers. The addition of as much as 1.5 kilometers of Lamotte Sandstone could raise that amount to 7.8 kilometers for pre-Cretaceous strata.

Fluid inclusion homogenization temperatures provide estimates of the minimum temperatures for sparry dolomite precipitation. Pressure corrections for these data in the Ozark and Nashville domes are probably no more than 15°–20°C, whereas in the Reelfoot rift, corrections to the homogenization temperatures may be as high as 45°–60°C. Uncertainties regarding actual fluid pressures limit interpretation of the homogenization data. Nevertheless, the data provide important constraints on the thermal regime in the Reelfoot rift complex in late Paleozoic time.

Fluid inclusion homogenization temperatures in sparry dolomite from the Reelfoot rift complex are at least 60°C to more than 100°C hotter than in cathodoluminescent correlative sparry dolomite from the Ozark and Nashville domes. Conodont thermal-alteration indices in Lower Ordovician rocks in the Reelfoot rift are consistent with a minimum paleothermal burial gradient of about 30°C/km. Fluid inclusion homogenization temperatures from sparry dolomite in the Reelfoot rift are about 40°C higher than the minimum burial temperatures estimated from conodont thermal alteration. Pressure corrections to the homogenization temperatures could increase this difference by an additional 30°–50°C. This difference may reflect the fact that conodont thermal-alteration values are estimates of the *minimum* burial temperature achieved by the rocks. Fluid inclusions, however, may record the passage of transient but higher temperature fluids or a short-lived thermal pulse from igneous activity.

One of the most significant findings in this study is the high fluid inclusion temperatures recorded in sparry dolomite from the Reelfoot rift. Homogenization values in the deepest part of the Dow Chemical #1 Wilson drill hole (present depth of 3.66 km) are in the range of 150°–280°C; most of the data are in the range 220°–260°C. Applying a 60°C pressure correction, the actual temperatures achieved in the deepest part of Dow Chemical #1 Wilson drill hole could be in the range of 210°–340°C. This range would be equivalent to burial geothermal gradients of approximately 35°–60°C/km. The high fluid inclusion temperatures reflect either the temperatures of advecting hydrothermal brines or thermally reequilibrated fluid inclusions in response to higher basement-derived, conductive geothermal gradient. Widespread igneous activity in the Reelfoot rift complex in Late Pennsylvanian to Permian time may be responsible for the unusually high temperatures recorded by the fluid

inclusions. In either case, the fluid inclusion data point to a thermal event in the central Reelfoot rift where temperatures reached 300°C in the Bonneterre Formation.

In Dow Chemical #1 Wilson, high homogenization temperatures and relatively low salinities of many fluid inclusions from zone 3 dolomite from the Bonneterre Formation suggest the presence of a hotter and more dilute fluid component in the Reelfoot rift. Fluid inclusion data from other samples in the study area generally show significant but independent variation between homogenization temperature and salinity. These variations in temperature and salinity may reflect transient variations in fluid flow or fluid mixing within the Ouachita basin complex. However, the salinity-temperature relationship for samples from the New Madrid test well shows significantly greater variation in temperature relative to salinity, suggestive of post-trapping stretching or thermal reequilibration of the fluid inclusions.

INTRODUCTION

The Ozark region of the United States midcontinent is host for the largest Mississippi Valley–type (MVT) lead-zinc province in the world. This region, located north of the Ouachita foldbelt and covering more than 240,000 km^2, includes the world-class MVT districts of Old Lead Belt, Viburnum Trend, and Tri-State, and the smaller Northern Arkansas, Central Missouri, and Southeast Missouri barite districts (fig. 1). Leach and Rowan (1986) presented evidence that brine migration from the Arkoma foredeep (fig. 1), in response to Late Pennsylvanian–Early Permian orogenesis in the Ouachita foldbelt, was responsible for the formation of MVT deposits in the Ozark region. However, we are becoming increasingly convinced that a major component of fluid flow for the lead-rich deposits in the Viburnum Trend and Old Lead Belt in southeast Missouri was from the Reelfoot rift zone (Farr and Land, 1985; Farr, 1989a, 1989b; Erickson and others, 1988; Diehl and others, 1991; Goldhaber and Mosier, 1989; Viets and Leach, 1988, 1990; Horrall and others, 1993). In addition, Shelton, Bauer, and Gregg (1992) suggested the possibility of brine migration from the Illinois basin.

We report herein a reconnaissance fluid inclusion study of epigenetic sparry dolomite from Upper Cambrian and Lower Ordovician strata in two drill cores located in the Reelfoot rift complex, drill cores along the southeastern flank of the Ozark dome and the western flank of the Nashville dome, and samples from a rock quarry in northern Arkansas. In addition, conodont thermal-alteration studies were conducted where possible to provide additional thermal constraints. The fluid inclusion data, combined with conodont thermal-alteration studies, indicate that hot and highly saline brines were present in the Reelfoot rift complex during the Paleozoic. Cathodoluminescent (CL) zoning in sparry dolomite from the Reelfoot rift is similar to zoning in sparry dolomite in the Ozark region that is closely associated with MVT sulfide deposition. If the sparry dolomite studied in this report is temporally related to sparry dolomite in the Ozark region, then these data provide insights into the possible ore-fluid migration with respect to the tectonic history of the rift complex. Because many of our interpretations are based on previous studies of fluid inclusions and sparry dolomite in the Ozark region, we summarize the most important aspects of these earlier reports. In addition, we present a brief overview of the complex geology and tectonics of the Reelfoot rift to provide insight into possible tectonic implications of our data.

ACKNOWLEDGMENTS

We appreciate the many helpful discussions and suggestions from John Viets, Jim Palmer, Anita Harris, and Albert Hofstra. Many of the samples were obtained from the Missouri Geological Survey with the help of Jim Palmer. David Weary's help was invaluable in processing the ARK-DW (Dow Chemical #1 Wilson) and Imboden samples. The manuscript was significantly improved from constructive reviews by Martin Goldhaber, David Houseknecht, and J.A. Allan.

GEOLOGIC SETTING

Development of the Arkoma and Black Warrior foredeeps and the Ouachita foldbelt (fig. 1) is generally accepted to be the result of closure of a Paleozoic ocean basin. South-dipping subduction of the North American plate beneath a magmatic arc or continental plate formed an accretionary wedge and culminated in plate suturing (Viele, 1979; Nelson and others, 1982). This accretionary wedge and associated Ouachita foldbelt overlie the thick sedimentary fill of the Late Proterozoic–early Paleozoic Reelfoot rift basin. The eastward extension of the Arkoma foredeep forms a juncture with the Black Warrior foredeep. This juncture, at present poorly understood, is buried beneath Cretaceous and younger rocks and sediments of the Mississippi Embayment (Thomas, 1976). During late Paleozoic time, the Reelfoot rift basin was part of a more extensive basin that included the southern part of the Illinois basin and the Arkoma and Black Warrior foredeeps. This basin complex was bounded on the south by the frontal Ouachita fold belt and to the southeast by

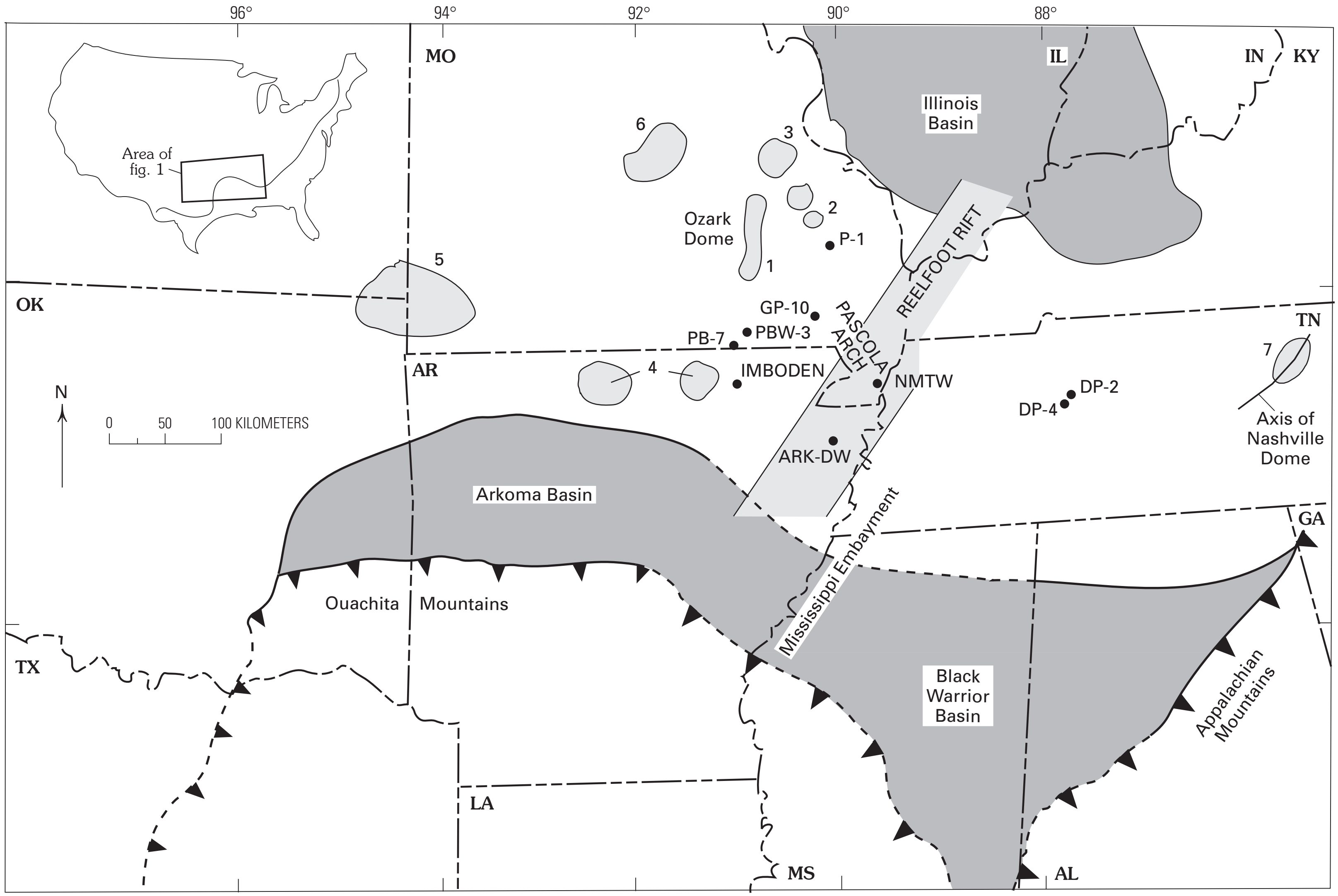

Figure 1. Location map showing drill holes, mining districts, major tectonic features, sedimentary basins, and likely ore fluid flow-paths in the Ozark region. MVT districts: 1, Viburnum Trend subdistrict of southeast Missouri; 2, Old Lead Belt subdistrict of southeast Missouri; 3, Southeast Missouri Barite; 4, Northern Arkansas; 5, Tri-State; 6, Central Missouri. Sawteeth represent fold belts. NMTW, New Madrid test well; ARK-DW, Dow Chemical #1 Wilson hole.

the southern Appalachian fold belt. Mississippi Valley–type fluids may have migrated from the eastward portion of the Arkoma basin or from the tectonically related Black Warrior foredeep northward through the Reelfoot rift complex into the Southeast Missouri lead districts.

The Reelfoot rift (fig. 1), buried beneath approximately 1 km of Cretaceous to Holocene rocks and sediments of the Mississippi Embayment, is generally thought to be a late Precambrian to Early Cambrian failed continental rift that formed during supercontinent rifting that led to the formation of the Paleozoic Iapetus ocean (Ervin and McGinnis, 1975; Kane and others, 1981; Kolata and Nelson, 1991; Nelson and Zhang, 1991). Nelson and Zhang (1991) showed that the total sedimentary fill of the Mississippi Embayment is variable in thickness and ranges from about 4 to 8 km in depth. Subsidence of the rift along steeply dipping bounding faults resulted in the accumulation of as much as 1.5 km of probable syn-rift sediments of the Lamotte Sandstone (Late Cambrian age) (Nelson and Zhang, 1991). Active rifting ceased, probably by Middle to Late Cambrian, and the Reelfoot region evolved into a sag basin by Late Cambrian. Continued subsidence of the Reelfoot basin continued into the late Paleozoic, with interspersed episodes of mild deformation and uplift along the margins of the North American craton during Paleozoic orogenies. Post-rifting subsidence extended beyond the rift bounding faults and formed a broad sedimentary sag basin that overlies the Reelfoot graben. Post-rift Cambrian and Ordovician sedimentary rocks, described by Nelson and Zhang (1991), include the stratigraphic units they assigned to the Bonneterre Formation, Elvins Group, and Knox Group. These sediments and rocks are thickest (2.7–3 km) within the rift and thin to about 2.1 km on the southeast shoulder of the rift (Nelson and Zhang, 1991). Little is known about the original thickness of post-Knox sediments because of extensive erosion during Late Pennsylvanian–Permian uplift of the northern Reelfoot rift. Schwalb (1982) estimated that at least 2.8 km of post-Knox through Pennsylvanian sediments accumulated in the northern Reelfoot zone. Thus, by Late Pennsylvanian, about 7 km of Paleozoic rocks filled the central rift basin. As a consequence of crustal downwarping during the Ouachita orogeny, Pennsylvanian sediments are likely to thicken southward to the juncture with the Ouachita fold belt. Therefore, in the southern part of the Reelfoot rift complex, the total thickness of Paleozoic rocks could exceed 7 km.

Late Paleozoic to Mesozoic uplift resulted in the formation and subsequent erosion of the Pascola arch (Kolata and Nelson, 1991), which trends northwest-southeast and forms the southern end of the Illinois basin (fig. 1). The late Paleozoic to Mesozoic uplift in the Reelfoot rift is reflected by the fact that the pre-Mt. Simon/Lamotte Sandstone underlies the Cretaceous unconformity at the crest of the Pascola arch (Schwalb, 1982). Stearns and Marcher (1962) suggested that between 2.5 and 4.5 km of Paleozoic rocks were eroded during uplift of the Pascola arch. Another large antiformal structure, called the Blytheville arch, parallels the trend of the Reelfoot rift and may connect with the Pascola arch (McKeown and others, 1990). The nature of these structural highs is of considerable interest because most earthquakes in the New Madrid seismic zone are associated with the trend of these structures (Hildenbrand and others, 1977), and uplift of the arches may have influenced migration of MVT ore fluids in late Paleozoic time. Howe and Thompson (1984), Hildenbrand (1985), Stearns and Marcher (1962), and Hamilton and McKeown (1988) suggested that the arches are tectonic features related to basement faulting; Howe (1985) and Nelson and Zhang (1991) directly related the arches to compressional forces during a late Paleozoic orogeny. Other proposed mechanisms include uplift as a consequence of igneous activity (Crone and others, 1985) and diapiric intrusion (McKeown and others, 1990).

Formation of the modern Mississippi Embayment began with subsidence of the Gulf Coastal Plain during breakup of Pangea in the Late Cretaceous (Caplan, 1954; Stearns and Marcher, 1962). West of Memphis, Tenn., Cretaceous sediment and rocks reach a thickness of 1 km.

Post-rifting igneous activity in the Reelfoot rift resulted in Late Pennsylvanian to Permian alkalic dikes and sills as indicated in drill core in the vicinity of the Pascola arch and in Hicks dome in the southern Illinois fluorspar district (Zartman, 1977). Hildenbrand (1985) used geophysical data to identify possible post-early Paleozoic intrusions along the margins of the Reelfoot rift.

SOUTHEAST MISSOURI LEAD DISTRICT

The Southeast Missouri lead district includes the major subdistricts of the Viburnum Trend and Old Lead Belt (fig. 1). The ore deposits are restricted to Upper Cambrian rocks, which unconformably overlie the Precambrian crystalline rocks of the St. Francois Mountains at the crest of the Ozark dome. About 95 percent of the ore has been produced from dolostones in the Bonneterre Formation (Upper Cambrian) and the remainder from the basal Lamotte Sandstone (Upper Cambrian). The Lamotte Sandstone is variable in thickness, ranging from 0 to 125 m, whereas the Bonneterre Formation averages about 90 m thick. The overlying Cambrian-Ordovician formations have an aggregate thickness of about 325 m (Gerdemann and Meyers, 1972). Cambrian and Ordovician rocks in the Southeast Missouri lead districts (about 500 m combined thickness) dramatically thicken southeastward into the Reelfoot rift zone, where these rocks may have a combined thickness of as much as 4.5 km.

Detailed descriptions of the mines of the Viburnum Trend are given in a series of papers in Economic Geology (v. 72, no. 3, 1977). Other important papers include Snyder and Gerdemann (1968), Gerdemann and Meyers (1972), and Sverjensky (1981).

SPARRY DOLOMITE IN THE OZARK REGION

Sulfide ore minerals in the Ozark MVT districts are associated with coarse, saddle-shaped, sparry dolomite that paragenetically spans deposition of ore minerals. This sparry dolomite is present as fractures and vug linings within secondary or secondarily enhanced porosity and as replacement of limestones. Distant from the ore districts, sparry dolomite may occur without associated sulfides but, as studied by Erickson and others (1981, 1988), commonly is closely associated with trace sulfides in ore-barren rocks. Palmer and Hayes (1989) used iron staining and a distinctive dolomite color sequence in the sparry dolomite to correlate specific paragenetic stages of sulfides in each ore district. They demonstrated that many stages of sulfides in each district and the widespread occurrences of sparry dolomite and trace sulfides are correlatable throughout the Ozark region, providing strong evidence for a large interconnected hydrothermal system for the Ozark region.

The iron staining and dolomite color sequence in sparry dolomite observed by Palmer and Hayes (1989) correlates with previously established cathodoluminescent (CL) microstratigraphy in sparry dolomite for the Ozarks (Voss and Hagni, 1985; Frank and Lohmann, 1986). Voss and Hagni (1985) established a CL microstratigraphy in sparry dolomite from the Viburnum Trend over a distance of approximately 30 km. Gregg (1985) identified the microstratigraphy in dolomite cements in the basal Bonneterre Formation as far as 80 km west of the Viburnum Trend district. Rowan (1986) observed correlative CL zonation a distance of 350 km to the southwest near the Tri-State and Northern Arkansas districts. Farr and Land (1985), Farr (1989b), and Shelton, Bauer, and Gregg (1992) expanded the microstratigraphy into southeastern Missouri and northern Arkansas, near the limit of the Mississippi Embayment.

The sparry dolomite microstratigraphy consists of four zones or bands (fig. 2), each consisting of subbands (Voss and Hagni, 1985; Voss and others, 1989). Zone 1 is typically moderately luminescent and is characteristically mottled. Zone 2, commonly not well developed and often difficult to identify, consists of very narrow, micron (micrometer)-width, regular bands; Frank and Lohman (1986) did not recognize zone 2 as a distinct band. Zone 3 consists of numerous alternating bright and dark bands, and zone 4 is characteristically dull to nonluminescent.

The oldest zone (1) and the youngest zone (4) bracket unambiguously main ore-stage sulfides (octahedral-galena stage) in the Viburnum Trend (Voss and others, 1989; Rowan and Leach, 1989). Zones 1 and 2 predate main-stage ore deposition. Zone 3 dolomite formed intermittently with episodes of main-stage sulfide deposition in the Viburnum Trend (Rowan and Leach, 1989, p. 1953). However, Voss and others (1989) considered zone 3 to be entirely post-main stage galena (octahedral galena) but predate late-stage galena (cubic galena). They considered zone 4 dolomite to have formed after late-stage galena, whereas Rowan and Leach (1989) observed zone 4 dolomite to both predate and postdate deposition of cubic galena. In other Ozark MVT districts, we have observed that zone 3 dolomite, where present, was deposited prior to main-stage sphalerite and galena, whereas zone 4 dolomite was deposited both intermittently with, but mostly after deposition of main-stage sulfides. It appears that zone 3 dolomite is temporally related to deposition of main-stage ores in southeast Missouri, whereas zone 4 dolomite corresponds to the time of deposition of late-stage sulfides in southeast Missouri and main-stage ores in the other Ozark MVT districts.

Where recognition of the CL zone that hosts a fluid inclusion in sparry dolomite is possible, the CL microstratigraphy provides a relative time frame that facilitates comparison of fluid inclusion data from different samples. However, correlation of a particular band can be difficult. The thickness of the zone can be highly variable because of limited crystal growth and (or) orientation of sections relative to the direction of crystal growth; zones may also be completely absent.

AGE OF SPARRY DOLOMITE CEMENT

In view of the paragenetic association of regional sparry dolomite with the MVT deposits in the Ozark region, the age of MVT ore formation should also broadly reflect the time of deposition of ore-stage sparry dolomite in the study area. Recent attempts to date MVT mineralization in the Ozark region have been mainly by paleomagnetic methods using apparent polar wandering paths (Wisniowiecki and others, 1983; Pan and others, 1990; Symons and Sangster, 1991, 1994). The paleomagnetic results yield a regionally consistent age of Late Pennsylvanian to Permian. Consistent with the paleomagnetic results, isotopic studies in the U.S. midcontinent region indicate an episode of regional hydrothermal fluid migration and formation of MVT deposits in late Paleozoic time (Hay and others, 1988; Desborough and others, 1985; Bass and Ferrara, 1969; Shelton and others, 1986; Aronson, reported in Rothbard, 1983; Brannon and others, 1992; Chesley and others, 1994; Brannon and others, 1995). In view of the late Paleozoic to Early Permian age for MVT ore deposition, we suggest that the ore-stage sparry dolomite was deposited at this time. In contrast to the Late Pennsylvanian to Permian ages, other isotopic studies in the midcontinent indicate additional widespread fluid migrations and precipitation of authigenetic minerals in Late Devonian and Early Devonian time, which are possibly associated with earlier North American orogenies. (See, for example, Hay and others, 1988; Posey and others, 1983; Stein and Kish, 1985, 1991; Duffin and others, 1989.)

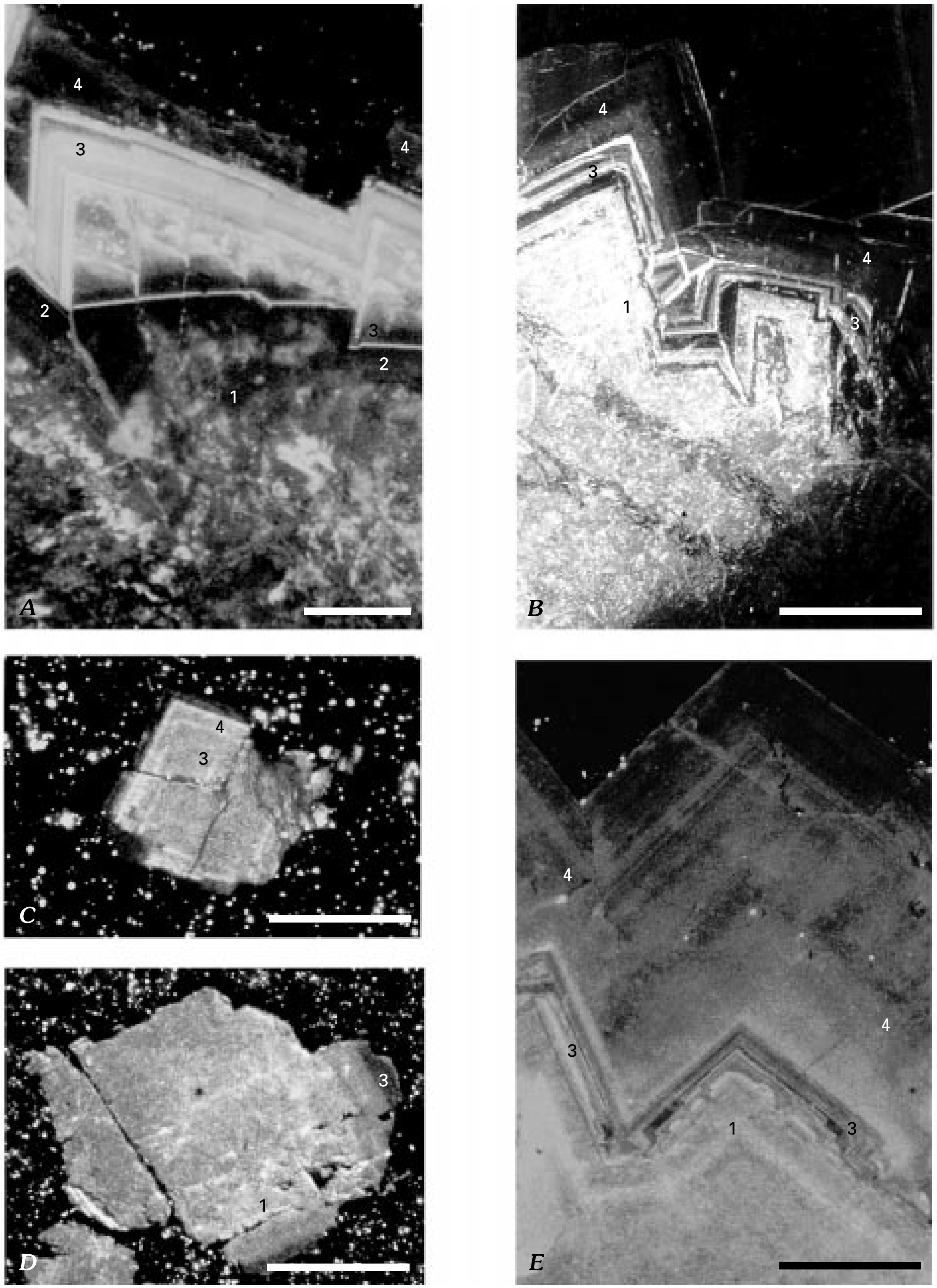
4
3
4
2
3
2
1
A
4
3
4
1
3
B
4
3
C
3
1
D
4
3
4
1
3
E

Figure 2 (previous page). Cathodoluminescent zones of dolomite from drill cores in Missouri, Arkansas, and Tennessee. Zone 1 is the earliest generation of dolomite, showing a moderate luminescence, a mottled texture, an absence of banding, and a gradational contact with the host rock. Zone 2 is not well defined, consisting of narrow micron (micrometer)-width bands with a dull luminescence. Zone 3 contains numerous alternating bright and dark subbands. Zone 4, the outermost zone, is dull to nonluminescent. This zoning is consistent with the dolomite cathodoluminescence microstratigraphy defined for the Viburnum Trend (Voss and Hagni, 1985; Voss and others, 1989; Rowan, 1986). *A*, Buick Mine, Missouri; typical of the Viburnum Trend cathodoluminescent stratigraphy; zone 2 is not well developed. Scale bar = 0.2 mm. *B*, GP-10, southeast Missouri; stratigraphy similar to that seen in the Viburnum Trend. Scale bar = 0.4 mm. *C*, ARK-DW-12,000, Arkansas; grain mount. Zone 3 observed most often, consisting of alternating dull and bright bands. Scale bar = 0.08 mm. *D*, NMTW-2,055, Missouri; grain mount, predominantly zone 3 banding with some zone 1 (mottled). Scale bar = 0.12 mm. *E*, DP-4, Tennessee; shows zonation similar to that seen in the Viburnum Trend. Symmetry of banding is not as well developed. Scale bar = 0.4 mm.

TEMPERATURE, SALINITY, AND COMPOSITION OF THE MVT FLUIDS IN THE OZARK REGION

Studies of MVT ore minerals and associated sparry dolomite in the Ozark region show that the mineralizing fluid was a brine at temperatures predominantly between 80° and 140°C (see references in Leach and Rowan, 1986; Rowan and Leach, 1989; and Shelton, Bauer, and Gregg, 1992). Final ice-melting temperatures of fluid inclusions in samples throughout the Ozark region (Leach and others, 1975; Leach, 1979; Leach and Rowan, 1986; Rowan and Leach, 1989) range mainly from –10° to –27°C, with a well-defined mode at –21°C, corresponding to 23 equivalent weight percent NaCl. These studies show a range of final ice-melting temperatures with a small secondary mode at around –10° to –15°C, corresponding to salinities of 14–18 equivalent weight percent NaCl. Rowan and Leach (1989) proposed that this secondary mode of final ice-melting temperatures is evidence for another, more dilute brine present in the region during mineralization, consistent with Bauer and Shelton (1989) and Shelton, Bauer, and Gregg (1992). Recent studies by Bauer and Shelton (1989) and Shelton, Bauer, and Gregg (1992) on sparry dolomite from the Ozark region indicated a larger range in homogenization and final ice-melting temperatures than had been previously reported.

THERMAL REGIME OF THE REELFOOT RIFT

In a recent study by Shelton, Haeussler, and Burstein (1992), fluid inclusion homogenization temperatures of 180°–250°C were measured in sparry dolomite from the Bonneterre Formation at 2–3 km depth within the Reelfoot rift. Tobin (1991) presented fluid inclusion homogenization temperatures from sparry dolomite and calcite cement in the Bonneterre Formation from the Amoco No. 1 Spence Trusts well in the Reelfoot rift. These samples were from present depths of about 2.3–2.4 km. Homogenization temperatures range from a mean of 235°C for primary inclusions in sparry dolomite to a mean of 169°C for primary and secondary fluid inclusions in calcite cement; these temperatures are consistent with thermal alteration indices (TAI) of palynomorphs. Tobin (1991), assuming that these fluid inclusions were trapped at shallow depths (and low temperature) and that they had subsequently "reequilibrated" during burial to higher temperatures, used these data to derive a burial history of the Bonneterre Formation. Judging from Tobin's petrographic descriptions, his samples appear to be similar to sparry dolomite studied in this report.

METHODS AND RESULTS

SAMPLES OF SPARRY DOLOMITE

Samples of sparry dolomite were obtained from the USGS New Madrid Test Well (NMTW) and the Dow Chemical #1 Wilson (ARK-DW) drill core located in the Reelfoot rift (fig. 1). Other samples were obtained from drill core (PB-7, P-1, GP-10, and PBW-3) located on the southeastern flank of the Ozark dome and from a drill hole (DP-4) on the western flank of the Nashville dome. Samples were also collected in northeastern Arkansas at the Black Rock Quarry near Imboden, Ark. (JR-series). The sample set consists of sparry dolomite cement from Upper Cambrian to Lower Ordovician carbonate rocks (see appendix). For samples of sparry dolomite in drill core, pairs of polished thin sections were prepared from samples from selected depths; of each pair, one was used for CL examination and one for fluid inclusion study. However, most of the samples of sparry dolomite were obtained from insoluble residues of acetic acid digestions of the host rock obtained for studies of conodonts. Surprisingly, sparry dolomite crystals were only moderately corroded by acid digestion of the host limestones and dolostones. Grain mounts of hand-picked sparry dolomite were polished for CL and fluid inclusion studies. For each sample, a description of the CL zone(s) was documented. In separate polished plates, fluid inclusions were studied by microthermometry and their locations within the crystals carefully documented with photomicrographs. After completion of the fluid inclusion microthermometry, the CL zone that hosted the inclusions was determined. Identification of the CL zone hosting the fluid inclusions was made after fluid inclusion measurements, because the electron beam used in CL analysis produces more than sufficient heat to stretch or decrepitate the inclusions.

CATHODOLUMINESCENT MICROSTRATIGRAPHY

Recognition of a CL zone that hosts a fluid inclusion in sparry dolomite aids in determining a relative time frame that facilitates comparison of fluid inclusion data from different samples. For the Ozark region, where the CL microstratigraphy is well established, this comparison is relatively straightforward but requires the assumption that the CL zones are recording a fluid flow event that was broadly contemporaneous. However, extrapolating the Ozark CL microstratigraphy into areas adjacent to the Ozark region is admittedly less certain.

The samples of sparry dolomite used in this study exhibited CL zones similar to those observed in the Ozark region. The microstratigraphy was generally simpler, with fewer subbands, and many of the CL zones were thinner than those observed in the Viburnum Trend. For many samples, only two or three zones could be identified with confidence. As in the Ozark region (Rowan, 1986; Rowan and Leach, 1989), zone 2 dolomite was generally difficult to identify with confidence. The dull to moderately luminescent zone 1 dolomite was commonly the thickest CL zone in samples from the deepest part of the Reelfoot rift. In addition, the highly banded CL zone identified as zone 3 in our samples was generally thinner and contained fewer subbands relative to typical zone 3 dolomite in the Viburnum Trend. The dull to nonluminescent zone 4 dolomite likewise was thinner in our samples than in samples typically collected in the Ozarks.

Although there are minor differences in the CL zones (for example, thinner zones 3 and 4) in many of our samples compared to samples from the Viburnum Trend, we suggest that CL zones in our samples of sparry dolomite can be correlated with the CL microstratigraphy established for the Ozark region. In samples from the southern Ozark dome, this correlation is consistent with previous studies. Using this correlation as a working hypothesis, we have placed constraints on the relative time of fluid entrapment for the fluid inclusion data presented in this study. In the absence of independent age constraints on the sparry dolomite, this requires two assumptions: (1) that we have correctly identified the CL zones, and (2) that a primary fluid inclusion hosted in a particular CL zone in sparry dolomite from the Reelfoot rift, for example, trapped a sample of fluid from the same hydrological system that deposited the comparable zone in sparry dolomite from the Ozark region. In view of the evidence for the migration of MVT ore fluids out of the Reelfoot rift into the Ozark region, we find the latter assumption to be reasonable.

Sparry dolomite from drill holes PB-7, P-1, GP-10, and PBW-3 located on the southern and southeastern flank of the Ozark dome (fig. 1) are from the Upper Cambrian Bonneterre and Derby–Doe Run Formations (see appendix). All four CL zones were observed in samples from these drill holes (fig. 2*B*); however, zone 2 was commonly absent or difficult to identify with confidence. Samples from the Black Rock Quarry at Imboden, Ark., contain pink sparry dolomite characteristic of the Northern Arkansas and Tri-State districts. The CL zones were predominantly zone 4, with occasional crystals showing zone 3.

Samples studied from drill hole DP-4, located on the western flank of the Nashville dome (fig. 1), are from the Conasauga Group (Middle to Upper Cambrian). Distinctive in these samples are zones 1, 3, and 4 (fig. 2*E*). The CL zones in sparry dolomite from DP-4 are distinct from the CL microstratigraphy described by Kopp and others (1986) in sparry dolomite from Lower Ordovician rocks in the Central and East Tennessee districts. The CL zones in samples from DP-4 are also different from those observed in sparry dolomite in Lower Ordovician rocks in north-central Tennessee, described by Gorody (1980). We also examined CL zones in two drill cores from sites located approximately 20 km east of DP-4. In these samples, we did not observe CL zones that we could correlate with the Ozark CL microstratigraphy. Rather, the CL bands are most similar to those described in the Central Tennessee district (Kopp and others, 1986). We conclude that the Ozark hydrothermal system may have extended as far east as DP-4 on the Nashville dome (fig. 1).

Samples of sparry dolomite from the ARK-DW drill hole in the Reelfoot rift complex were obtained from acid insoluble residues of the Upper Cambrian Bonneterre Formation (depths of approximately 3.58–3.72 km (11,726–12,200 ft[1])), the Upper Cambrian Elvins Group (depths of approximately 3,250–3,575 m (10,660–11,726 ft)), and the Upper Cambrian–Lower Ordovician Knox or Arbuckle Group. CL zones 1, 3, and 4 were readily identified (fig. 2*C*); zone 2 was either not present or difficult to identify with confidence. Although zone 3 dolomite was observed throughout most of the drill hole, the most abundant and best developed zone 3 dolomite was found in the Bonneterre Formation at depths between 3.62 and 3.66 km (11,880 and 12,000 ft). Dolomites containing zone 4 are absent from the Bonneterre Formation (3.62–3.66 km) and are best developed at shallower stratigraphic levels, 1.07–2.9 km (3,540–9,540 ft). These observations suggest that fluid migration at the ARK-DW site during zone 3 time was mainly in the lowermost Paleozoic section (Bonneterre Formation and probably in the underlying Lamotte Sandstone), whereas by zone 4 time, fluid migration was occurring at shallower levels and largely through the Knox or Arbuckle Group aquifers. Alternatively, sparry dolomite was not precipitated in the lower Bonneterre during migration of brines that deposited zone 4 dolomite. It is possible that the brines were not saturated with respect to dolomite or that permeability was occluded

[1]Original depths were measured in feet; feet are thus given here for completeness, along with metric equivalents.

in the lower part of the stratigraphic section during migration of brines in zone 4 time.

Samples of sparry dolomite from the NMTW (fig. 1) are from the Upper Cambrian carbonates (Bonneterre Formation) located on the Pascola arch 25 km north of the ARK-DW drill hole. These samples were obtained from acid insoluble residues at drill hole depths of 626–701 m (2,055–2,300 ft). Examination of the CL zones identified only zones 1 and 3 with confidence; zone 2 is generally not present or is difficult to identify (fig. 2*D*). Zone 4 dolomite was not observed in the Bonneterre Formation in the NMTW, which is consistent with the absence of zone 4 dolomite in the Bonneterre Formation in drill hole ARK-DW.

FLUID INCLUSION STUDIES AND THE LIMITATION OF FLUID INCLUSION DATA FOR DOLOMITE

Microthermometric studies were made on 303 primary fluid inclusions in samples of sparry dolomite, mostly from drill cores NMTW, ARK-DW, DP-4, and the JR series. Measurements were made on a Fluid Inc. gas-flow fluid inclusion stage. Temperature measurements of homogenization (Th) and final ice-melting temperatures (Tm) have a precision of ±1.0°C and ±0.2°C, respectively. Possible overheating of fluid inclusions and stretching of fluid inclusions during homogenization studies were carefully avoided. The data for each sample are given in the appendix. The number of inclusion measurements is small because of the difficulty in identifying primary inclusions in which the CL zone could be identified with confidence, and that had not obviously experienced changes in inclusion volume (for example, necking). Measurements were made more difficult by the small size of the inclusions, commonly less than 10 microns (micrometers) in long dimension.

The sparry dolomite crystals typically display cloudy cores produced by dense populations of fluid inclusions; these cloudy cores typically are bounded by outer clear growth zones that contain considerably fewer inclusions. The primary nature of the inclusions was largely established by their occurrence in three-dimensional arrays related to crystal growth (Roedder, 1984, p. 43) or along distinct growth bands.

Primary fluid inclusions provide estimates of the hydrothermal environment and composition of the fluid from which the crystal precipitated. However, post-entrapment changes in fluid inclusion density and composition can, in some cases, seriously limit the determination of actual trapping conditions and fluid composition. In addition, homogenization temperatures provide estimates of the *minimum temperatures* of fluid entrapment; pressure corrections are necessary to obtain actual trapping temperatures.

The most serious sources of uncertainty in the fluid inclusion studies presented include: (1) uncertainties regarding the actual fluid pressures at time of entrapment of the fluid and therefore actual trapping temperatures; and (2) changes in fluid inclusion size and density related to fluid inclusion necking, stretching, and decrepitation or leakage into or out of the inclusion.

NECKING OF THE FLUID INCLUSIONS

The necking of fluid inclusions was suggested by Rowan and Leach (1989) and Leach and Rowan (1993) to be an inherent problem in sparry dolomites from the Ozark region. In this study, we observed commonly abundant evidence for the necking of fluid inclusions in sparry dolomite. Necking typically produces several smaller, more equant-shaped inclusions from a larger, elongate or flat inclusion of higher surface area, commonly progressing to the point where no visible evidence of the process remains. If a vapor phase nucleates in the fluid inclusion before or during necking of the fluid inclusion, the original liquid/vapor ratios (and fluid density) will be altered by the necking process, resulting in scatter in the Th data. Freezing point depression, however, is not measurably affected. (See Roedder, 1984, p. 59–66 for a complete discussion.)

Most of the samples of sparry dolomite have a cloudy core consisting of abundant fluid inclusions that are believed to be primary because they occur in a three-dimensional array related to crystal growth (Roedder, 1984, p. 43). Within these cloudy cores, we commonly observed inclusions whose shapes and distributions indicated various stages of necking. Some inclusions were single-phase, liquid or gas, and others had clearly variable gas/liquid ratios. However, we also observed groups of inclusions with consistent gas/liquid ratios that yielded Th ranges of several tens of degrees. Barely detectable differences in gas/liquid ratios may equate to significant differences in volume of the gas phase and in Th. In CL zones 3 and 4, inclusions are less abundant, but necking appears to have been prevalent there as well. Although we carefully selected inclusions that were not visibly necked, we rarely found groups of inclusions that yielded Th ranges of ±10°C or less. From these observations, we suggest that necking has affected many more inclusions in sparry dolomite than is visually evident, and that it accounts for significant variability in Th in sparry dolomite reported here and in other studies from the Ozark region.

Whereas the effects of undetected necking cannot be quantified, a reasonable approach to the problem is to give less credibility to extreme values of Th and focus interpretations on temperatures where most of the data occur. We have arbitrarily chosen to make comparisons of the central tendency of the Th populations (median or 50th percentile) and well-defined modes in the Th distributions. Considering the large range of the Th data (from about 90° to 260°C), these comparisons appear to be a reasonable but admittedly imprecise approach to the problem of undetected necking in the sparry dolomites.

CORRECTIONS TO HOMOGENIZATION TEMPERATURES FOR PRESSURE

If a fluid inclusion is trapped above a liquid-vapor curve, a correction for pressure must be made to arrive at actual trapping temperatures. In the Ozark dome, the maximum burial depth at the time of dolomite precipitation is estimated to have not exceeded 1.5–2 km (Leach and others, 1975; Leach, 1979). Assuming hydrostatic pressures and a simple H_2O-NaCl fluid, the resulting pressure correction would not exceed approximately 15°–20°C.

Estimation of the burial depth at the time of sparry dolomite precipitation in the Reelfoot rift is much more problematic. The deepest samples from ARK-DW are at a drill hole depth of 3.6 km, which includes a kilometer of Cretaceous and younger coastal plain rocks and sediments above the erosional surface in Paleozoic rocks. Based upon conodont thermal alteration studies (discussed in more detail later), as much as 2.1–3.7 km of additional Paleozoic rocks could have been present at ARK-DW drill hole in the late Paleozoic; therefore, the total thickness of Paleozoic rocks overlying the deepest sample could have been as much as 6.3 km. At the location of the NMTW drill hole, situated on the Pascola arch, Stearns and Marcher (1962) estimated that between 2.4 and 4.6 km of Paleozoic rocks were removed by erosion during uplift of the arch. Our deepest sample from the NMTW is at 713 m and yields a maximum burial depth of 5.3 km. For fluid inclusions trapped above a liquid-vapor solvus, at estimated maximum burial depths of 5.3–6.3 km, a hydrostatic pressure correction could be as large as 45°–60°C. Burial depths of 4 km during fluid inclusion trapping would require as much as 30°–35°C correction to the observed homogenization temperatures. Therefore, the reported homogenization temperatures must be considered *minimum* estimates of the actual trapping temperatures.

Studies of gases in fluid inclusions from sparry dolomite in the Ozark region (Hofstra and others, 1989) suggest high amounts of CO_2 in the fluid inclusions. The anomalous concentration of CO_2 in the fluid inclusion gases together with mineralogical evidence for low pH between 4 and 5 of the fluids (Goldhaber and Stanton, 1987; Diehl and others, 1991) was interpreted to indicate that the dolomite-forming fluids may have been at or near saturation with respect to CO_2 and that effervescence was occurring during dolomite precipitation. Leach and others (1991) conducted chemical reaction path calculations for precipitation of sparry dolomite in the Ozark region. They concluded that near-isothermal effervescence of a CO_2-dominate gas phase during regional brine migrations to shallower burial depths was an attractive mechanism to account for the widespread occurrence of sparry dolomite in the Ozark region. If the fluid inclusions were trapped along a brine-CO_2 solvus, the homogenization temperatures record actual trapping temperatures and do not require a pressure correction. In the absence of independent data on the CO_2 content of the fluid inclusions in this study, we must assume that some unknown amount of pressure may be required to obtain actual trapping temperatures.

Considering the uncertainty surrounding the actual pressures during fluid trapping, the observed fluid inclusion data, especially from the Reelfoot rift, can only be compared on a broad basis from one location to another. A 2–4 km uncertainty in the actual depth of burial during fluid trapping yields about 15°–45°C uncertainty in the maximum correction to the observed homogenization temperatures.

CHANGES IN THE DENSITY OF INCLUSION FLUIDS DUE TO REEQUILIBRATION DURING POST-ENTRAPMENT BURIAL OR HEATING EVENTS

Several studies suggest that fluid inclusions in calcite can reequilibrate during post-entrapment burial or heating events (Goldstein, 1986; Prezbindowski and Larese, 1987; Burruss, 1987; see discussion in Goldstein and Reynolds, 1994), and presumably dolomite would respond in a similar manner. Such reequilibration can be useful in estimating the maximum temperature achieved by the sample during subsequent burial to greater depths (Prezbindowski and Larese, 1987; Burruss, 1987). The fluid inclusions examined in our study were trapped in Late Pennsylvanian to middle Permian time at or near their maximum burial depths. The post-entrapment burial history for our fluid inclusions included initial uplift (about 2.4–4.6 km for NMTW (Stearns and Marcher, 1962)—less for ARK-DW) followed by about 1 km of subsidence during sedimentation of the coastal plain sediments. Thus, net overburden has decreased since fluid inclusion entrapment, so burial reequilibration of the fluid inclusions is unlikely to have reset the homogenization temperatures.

A more likely source of the uncertainty in our fluid inclusion study is the possible reequilibration or stretching of the fluid inclusions caused by post-entrapment heating from igneous activity in the Reelfoot rift. Igneous activity in the Reelfoot rift includes emplacement of Late Pennsylvanian to Permian age alkalic dikes and sills in the vicinity of Hicks dome in the southern Illinois fluorspar district and in the Pascola arch (Zartman, 1977). Hildenbrand (1985) used geophysical data to identify possible post-rift intrusions along the margins of the Reelfoot rift. One of these inferred intrusions is about 30 km east of the ARK-DW drill hole. In addition, anomalous concentrations of Be, Nb, Th, and La (unpublished data from R.L. Erickson and M.B. Goldhaber) were recorded in portions of the NMTW drill core. This suite of elements is consistent with possible alkalic igneous activity (Goldhaber and others, 1992). Although rocks in the

NMTW have been geochemically altered, no clear evidence suggests that they have been thermally altered (M.B. Goldhaber, oral commun., 1992).

Magmatism, rather than local igneous intrusions, might have been extensive in the Reelfoot rift during Late Pennsylvanian to Permian time, as suggested by Lewis (1987). Extensive intrusive activity would likely result in above-average heat flow in the Reelfoot rift at a time broadly coincident with inferred time of sparry dolomite precipitation. As discussed in the section about estimating paleotemperatures from thermal alteration of conodonts, an above-average heat-flow in the Reelfoot rift could account for the elevated homogenization temperatures reported here—including the possibility for stretching and reequilibrating of earlier trapped fluid inclusions.

If the fluid inclusions were stretched by post-entrapment heating, we might have observed a correlation of fluid inclusion size with Th or gas/liquid ratios; stretching of fluid inclusions during post-entrapment heating is more likely to affect larger inclusions (Bodnar and Bethke, 1984). We did not observe any correlation of Th or gas/liquid ratios with inclusion sizes that range from 5 to 30 microns (micrometers), which would indicate post-entrapment stretching. However, as discussed later, certain evidence from the observed homogenization temperatures from samples in the rift may reflect post-entrapment stretching of the fluid inclusions.

LEAKAGE INTO OR OUT OF THE FLUID INCLUSIONS DURING POST-ENTRAPMENT THERMAL DECREPITATION

Partial to complete recrystallization of the dolomite can result in formation of new primary fluid inclusions in the host crystal. This could produce a range of homogenization and ice-melting temperatures that reflects the conditions of fluids in which recrystallization occurred. In our samples, we did not observe any textural evidence (such as disrupted or altered CL bands) that suggests recrystallization of the host dolomite occurred. However, the decrepitation of fluid inclusions during post-entrapment thermal events and the infilling by new fluids are a possible concern in the Reelfoot rift samples. If this process occurred in our samples, we would expect to see a range in homogenization and ice-melting temperatures as well as fractures and fluid inclusion textures indicative of decrepitation. Although we did not observe textural evidence for decrepitation, the fluid inclusion data from dolomite in the Reelfoot rift show a wide range in salinity and filling temperatures. Therefore, we cannot exclude the possibility that decrepitation of fluid inclusions and the infilling by new fluids did take place.

ESTIMATES OF PALEOTEMPERATURES FROM THERMAL ALTERATION OF CONODONTS IN THE ARK-DW DRILL HOLE

Conodonts were not present in the NMTW because the host rocks are Upper Cambrian Bonneterre Formation, below the common occurrence of euconodonts (or true conodonts). Studies of conodont thermal-alteration indices (CAI) in post-Bonneterre rocks in the ARK-DW drill hole provide constraints on paleothermal gradients in the rift (J.E. Repetski, unpub. data, 1992). In the samples from the ARK-DW drill hole, conodont CAI values are consistent with normally progressive downhole temperatures, and surface corrosion of the conodonts is not obviously greater than what would be expected by diagenetic dolomitization at some of the collection horizons. For example, the conodont elements do not show several CAI values in any one sample, nor do they exhibit abnormal appearance of whitened margins or patinas, as would be expected from significant exposure to hydrothermal fluids. (See, for example, Rejebian and others, 1987.) At 914 m the CAI is 23, indicating a *minimum* burial temperature of about 100°C, whereas at 2.59 km the CAI is $3^1/_2$, equivalent to a *minimum* burial temperature of about 150°C (assuming 25°C ambient surface temperature). These inferred temperatures indicate a burial thermal gradient of about 30°C/km. Because the CAI is a time-dependent indicator, a short-lived thermal event of less than 1 m.y. in the Reelfoot rift might be undetected in the conodont CAI.

If the CAI values found in the ARK-DW drill hole only reflect burial temperatures, then we can estimate the amount of post-Early Ordovician, pre-Cretaceous-age strata that have been present in this part of the rift. The overburden needed to generate a CAI of $2^1/_2$–3, as found at the top of the preserved Paleozoic succession, at 914 m in the ARK-DW drill hole, is about 3,049–4,573 m, given a burial thermal gradient of about 30°C/km and given the existence of this amount of burial for at least 1 m.y. before subsequent erosion (Epstein and others, 1977; Harris, 1979). By this reasoning, at least 2,134–3,659 m of Middle Ordovician and younger sediments were deposited in this part of the basin before the Cretaceous, and most likely before the middle Permian. The conodont CAI values may reflect a short-lived thermal event from advective heat transport by hydrothermal fluids or conductive heating from igneous intrusions rather than simple burial thermal gradients. In this situation, the amount of burial estimated solely on the CAI values may be too large. However, the consistent downhole CAI trend and the general absence of within-sample CAI, bleaching, or corrosion variations argue against significant effects from these nonburial heating sources.

The *minimum* burial temperatures estimated from conodont CAI values are at least 30°–50°C lower than homogenization temperatures from sparry dolomite at approximately the same stratigraphic positions. The observed homogenization temperatures are minimum

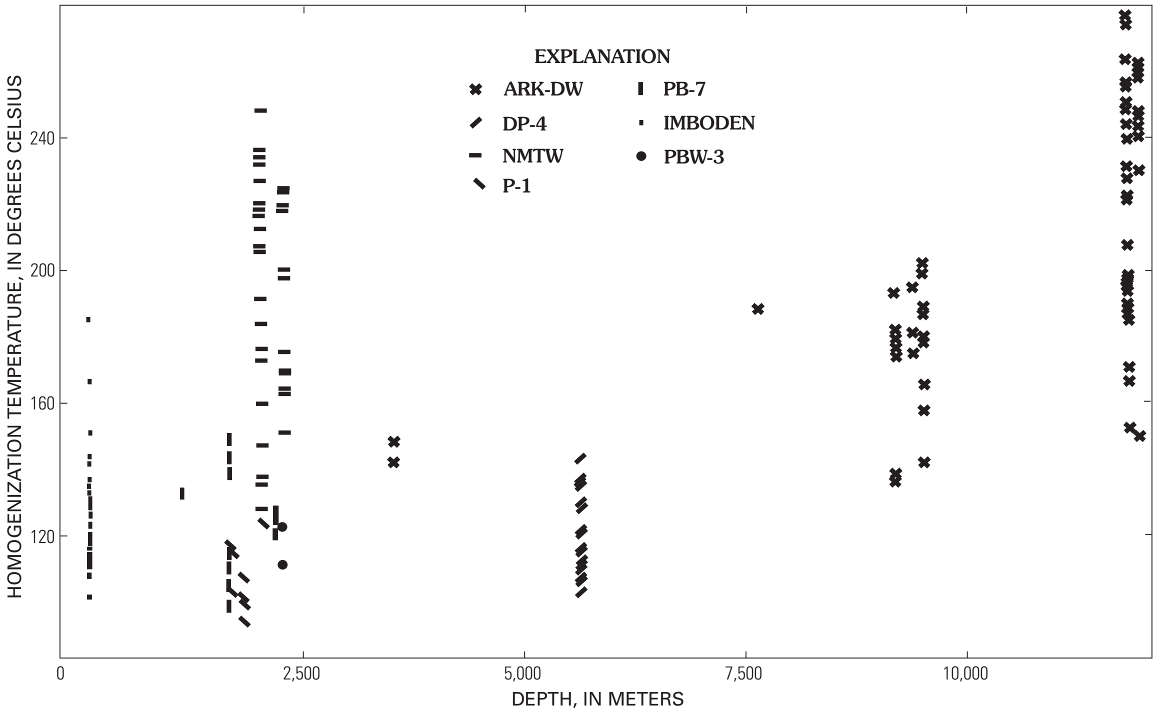

Figure 3. Homogenization temperature (Th) versus depth for all drill hole fluid inclusion data.

estimates of the temperatures (1) at which primary fluid inclusions were trapped or (2) at which thermal reequilibration may have occurred during a possible post-trapping thermal event. Therefore, the addition of pressure corrections to the homogenization temperatures could increase this difference by as much as another 30°–60°C. The most obvious possibility is that the conodont CAI values record the minimum burial temperatures of the rocks, whereas the fluid inclusions record a transient and short-lived thermal event of less than 1 m.y.

REELFOOT RIFT DRILL HOLES

The homogenization temperatures for fluid inclusions hosted in zones 3 and 4 dolomite from all drill holes are shown in figure 3. In view of the uncertainties related to unknown pressure corrections to the fluid inclusion homogenization values and uncertainties related to possible post-trapping changes in the density of the fluid inclusions, only general comparisons can be reasonably made between the different sample locations. Based on reasonable difference in the stratigraphic cover, maximum pressure corrections to the homogenization temperatures for data from the Reelfoot rift probably exceed by about 10°–40°C the maximum corrections to the data for samples from the Ozark and Nashville domes. The uncorrected Th values for the Reelfoot rift drill holes (NMTW and ARK-DW) are consistently higher than those on the flanks of the Ozark and Nashville domes. With the exception of fluid inclusions in samples from the NMTW, the data show a general trend of increasing homogenization with increasing depth where the samples were obtained.

Figure 4 shows the location of samples studied in the ARK-DW drill hole. The homogenization temperatures (Th) in figure 5 show a clear bimodal distribution, one population with a mode around 250°C and another at about 190°C. It is clear from figures 5 and 6 that the higher temperature mode consists of fluid inclusions hosted by CL zone 3 dolomites. As discussed in the cathodoluminescent microstratigraphy section, sparry dolomites with CL zone 3 occur throughout the ARK-DW drill hole but are best developed in the Bonneterre Formation at 3.62 and 3.66 km. Dolomites containing CL zone 4 are absent from the Bonneterre Formation but are common at shallower stratigraphic levels, 1.07–2.9 km. Fluid inclusions in zone 4 dolomite have distinctly lower homogenization temperatures with a mode of about 190°C and median value of about 180°C. The apparent difference in homogenization temperatures between zones 3 and 4 fluid inclusions could be about 50°C. If pressure corrections to the homogenization temperatures, due to the stratigraphic separation between zones 3 and 4 dolomite, are considered, the difference in temperatures could be about 60°C. These estimates are based on the assumption that the post-Lower Ordovician stratigraphic overburden was approximately the same for fluids that formed zones 3 and 4 dolomite. If the difference in post-Lower Ordovician overburden between dolomite-hosted zones 3 and 4 fluids were around

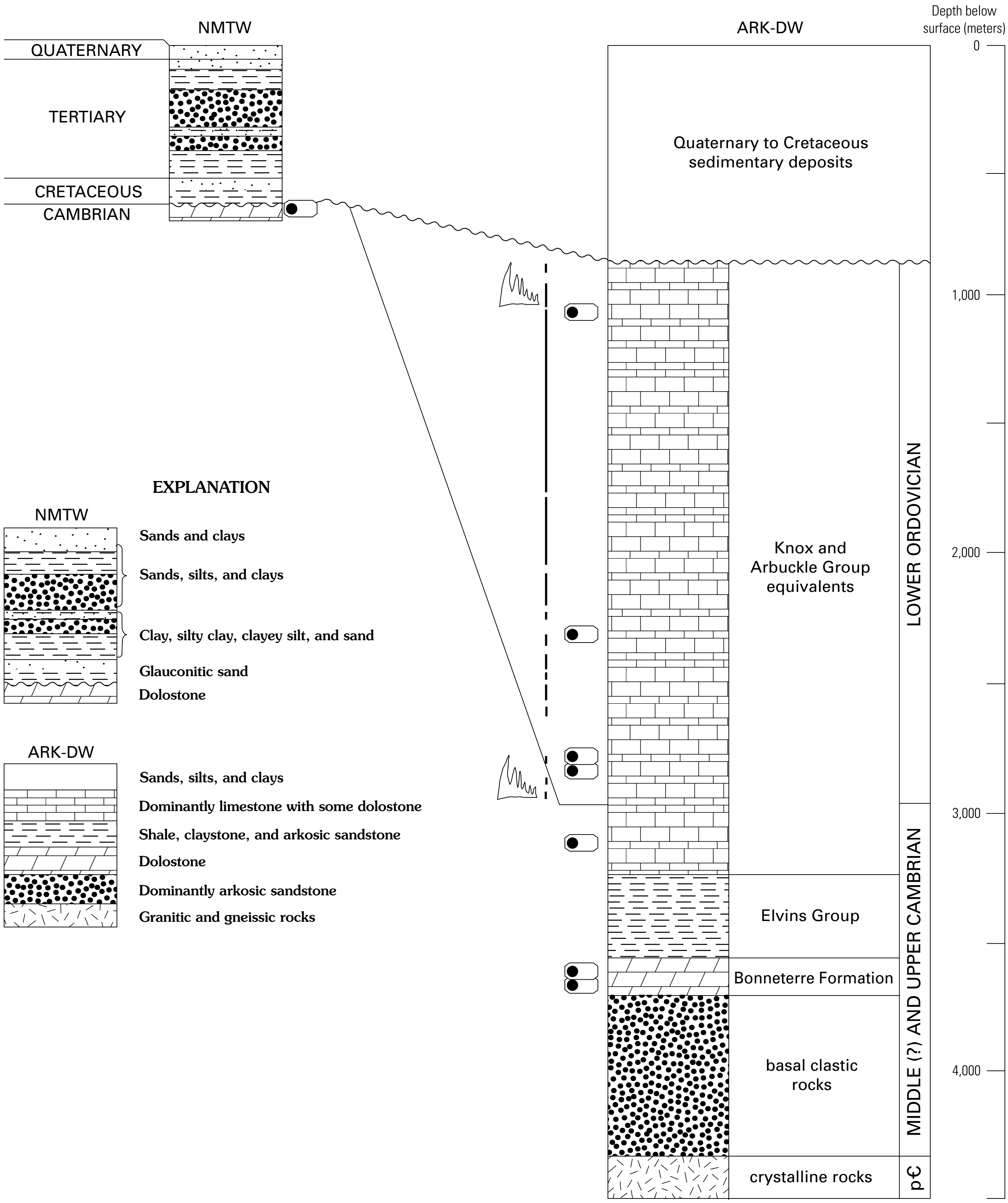

Figure 4. Idealized stratigraphic section for NMTW, Missouri, and ARK-DW, Arkansas, showing drill hole sample locations for fluid inclusions (oval with enclosed dot) and conodonts (toothed symbol). Wavy line, unconformity. Vertical solid and dashed line indicates distribution of conodonts.

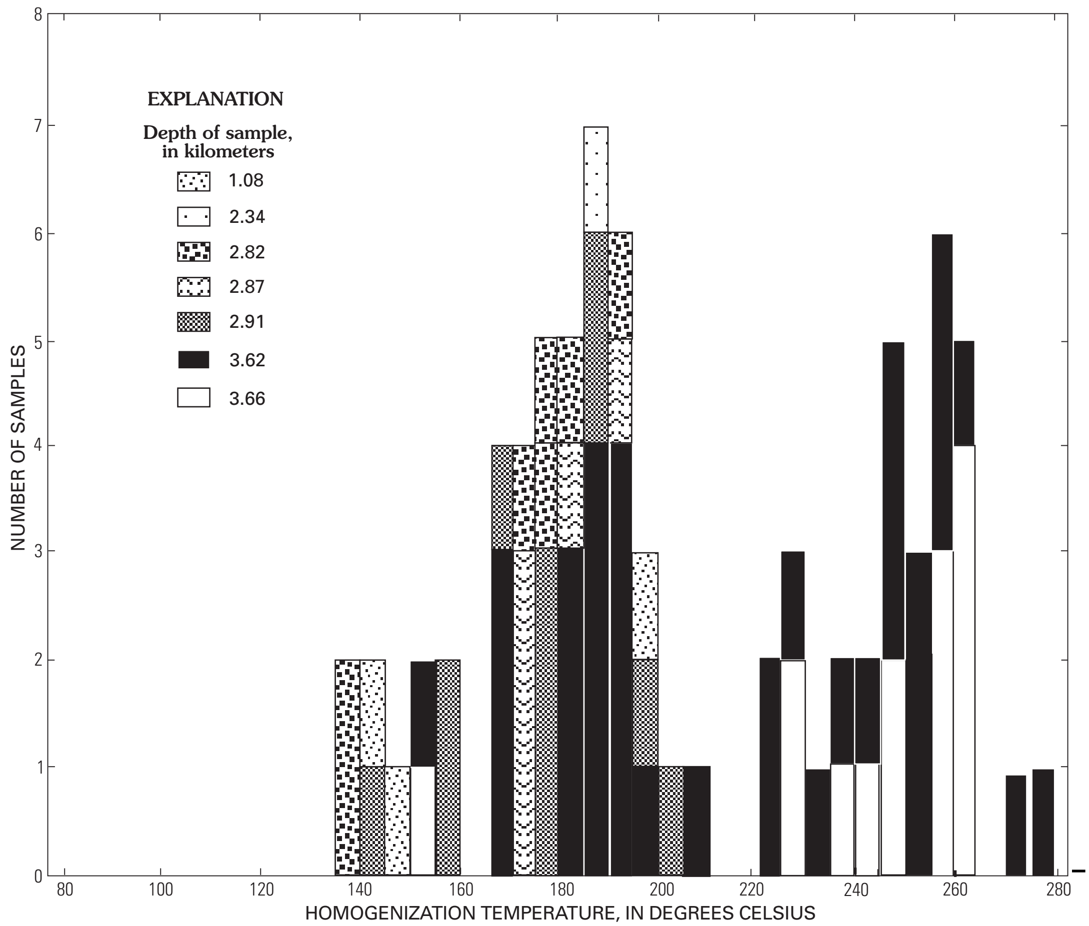

Figure 5. Histogram plot of homogenization temperature (Th) for ARK-DW drill hole. Variations in temperature with depth are also indicated.

3–6 km, the separation in observed homogenization temperatures could be due to pressure alone. In view of the inferred Late Pennsylvanian to Early Permian age for zones 3 and 4 dolomite, the difference in the amount of post-Lower Ordovician overburden between zones 3 and 4 dolomite was probably insufficient to account for the differences in the homogenization temperatures. Therefore, the separation between the homogenization temperatures for zones 3 and 4 fluid inclusions most likely reflects a real difference in the temperatures of the fluids that formed zones 3 and 4 dolomite.

All samples from the NMTW are from Upper Cambrian Bonneterre Formation, located on the Pascola arch 25 km north of the ARK-DW drill hole (fig. 1). Comparison of the distribution of Th values (range and median value) for zone 3-hosted fluid inclusions from both drill holes suggests temperatures in the NMTW could possibly have been slightly cooler than in the ARK-DW. However, in view of the uncertainty in pressures during fluid trapping, these slight differences in Th values may simply reflect different trapping pressures.

In addition, Th values from the NMTW do not conform to the broad trend of higher Th temperatures with greater drill hole depths (fig. 3) observed for the other locations. It appears that the Th values from samples in the NMTW are anomalously hot when compared to the Th-depth relations of ARK-DW (fig. 3). Dolomite from drill hole depths of 626–701 m in the Bonneterre Formation from the NMTW have Th values that correspond to values obtained from samples at drill hole depths of about 2.86–3.66 km in ARK-DW. All Th measurements in the NMTW and in ARK-DW at 2.86–3.66 km are from zone 3-hosted fluid inclusions.

In view of the uncertainties about pressure corrections and possible post-trapping changes in the fluid inclusion densities, the reason for the difference in Th values is speculative. One possibility is that the zone 3 dolomite in the NMTW formed from fluids at lower temperatures and pressures relative to the fluids in ARK-DW. In this case, zone 3 fluid migration would probably have occurred after uplift of the Pascola arch. The second possibility is that zone 3 dolomite in both drill holes formed at approximately the same

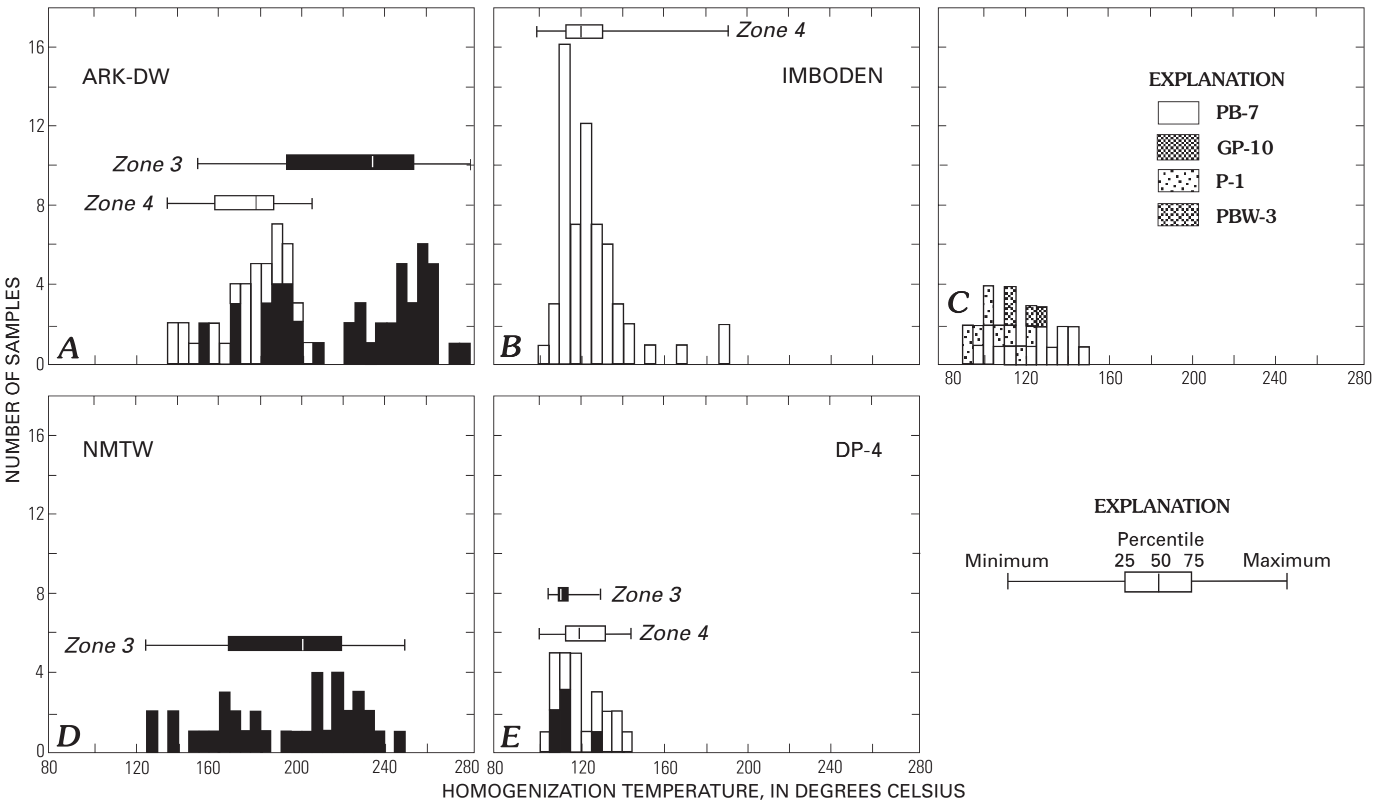

Figure 6. Histogram plots of homogenization temperature (Th). *A*, *B*, Ozark dome; *C*, *D*, Reelfoot rift; *E*, Nashville dome.

temperatures and pressures (burial depths) and the NMTW experienced a net uplift, relative to ARK-DW, of about 2.2–3 km. If the thickness of Paleozoic rocks deposited at the NMTW location were comparable to that at ARK-DW, as much as 4.3–6.7 km of Paleozoic rocks were eroded on the Pascola arch before the Cretaceous. A third possibility is that the fluid inclusions in zone 3 dolomite in the NMTW drill hole were stretched or thermally reequilibrated during a thermal event that could be related to the postulated igneous intrusion that produced the anomalous concentrations of Be, Nb, Th, and La in samples from the drill hole.

SAMPLES FROM THE OZARK DOME

All Th data from sparry dolomite from the Lower Ordovician Powell Dolomite in the Black Rock Quarry at Imboden, Ark. (figs. 3 and 6) are from zone 4-hosted fluid inclusions. Zones 1 and 3 were recognized, but we were unable to obtain Th measurements from these zones. The Th data from zone 4 dolomite at Imboden are essentially identical to the Th data from sphalerite from the Northern Arkansas district (Leach and others, 1975; Long and others, 1986).

Conodonts from the upper Lower Ordovician rocks at the Imboden Black Rock Quarry (J.E. Repetski, unpub. data, 1992) have CAI values of $1^1/_2$, indicating that they experienced minimum post-depositional heating in the range of 50°–90°C. Thus, the contrast in CAI values between the Reelfoot rift and Imboden demonstrates a trend consistent with the fluid inclusion data (as discussed in the following paragraphs).

Also shown in figure 6 are Th data from sparry dolomite from Upper Cambrian Bonneterre and Derby–Doe Run Formations in drill cores PB-7, GP-10, P-1, and PBW-3. The Th data from these samples include zones 1, 3, and 4. The few measurements from these samples prevent recognition of possible differences between the Th of the different zones, and we have chosen to combine them into a single histogram.

The Th values from sparry dolomite in the Ozark dome are clearly lower than from comparable sparry dolomite in the Reelfoot rift. For example, fluid inclusions in zone 4 dolomite from Upper Cambrian rocks in the ARK-DW drill hole have a median value of 180°C, whereas fluid inclusions in zone 4 dolomite from Lower Ordovician rocks 50 km northwest at Imboden, Ark., have a median value of 117°C. Thus, Th values differ by at least 60°C in fluid inclusions in samples of CL-equivalent sparry dolomite located 50 km apart and 2.87 km vertically (drill hole depths). Because of the clear difference in burial depths between the Ozark dome and Reelfoot samples, the pressure corrected Th values would indicate even greater difference in temperatures for fluid in the Reelfoot rift relative to the Ozark dome.

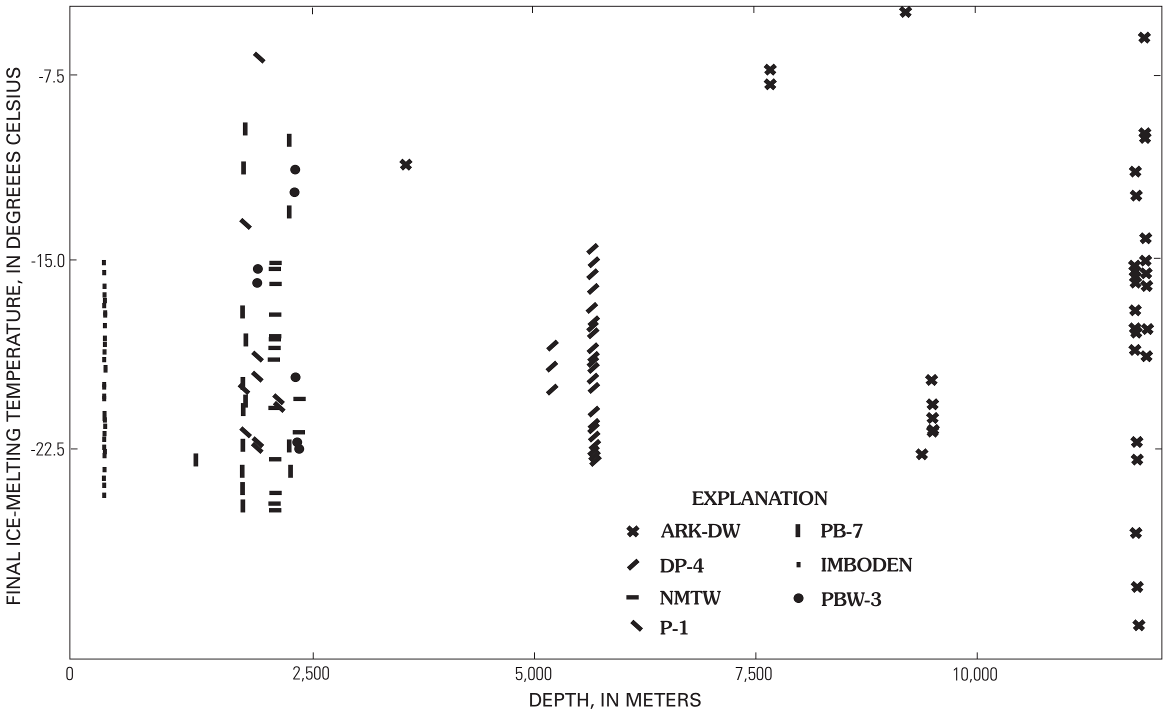

Figure 7. Final ice-melting temperature (Tm) versus depth for all drill hole fluid inclusion data.

NASHVILLE DOME

Samples of sparry dolomite containing CL zones 1, 3, and 4 were obtained from drill core DP-4 (fig. 1), located along the western flank of the Nashville dome. Only zones 3 and 4 yielded usable fluid inclusions for Th measurements (fig. 6). The data are from samples of sparry dolomite hosted by the Conasauga Group (Middle and Upper Cambrian). The present burial depth for the samples is 1.73 km. The Th values for zones 3 and 4 lie in the range of 100°–145°C and are similar to Th values for the Ozark dome. These observations are significant in that they show the Ozark MVT–Reelfoot rift hydrothermal system extended onto the western flank of the Nashville dome.

FINAL ICE-MELTING TEMPERATURES

Measurements of the final ice-melting temperatures of fluid inclusions for all samples range from –4.9° to –29.9°C (figs. 7 and 8), corresponding from 7.7 to greater than 23 equivalent weight percent NaCl (Bodnar, 1992). Although samples from ARK-DW show the largest spread in Tm, salinity does not differ significantly between locations, between present burial depths, or between fluid inclusions hosted by zones 3 and 4 dolomite. First-melting temperatures are lower than –50°C, indicating the presence of appreciable divalent ions in solution. These data are similar to data obtained in other studies of sparry dolomite (Rowan and Leach, 1989; Shelton, Bauer, and Gregg, 1992) and for sphalerite from MVT occurrences in the Ozark region (Roedder, 1967; Leach and others, 1975; Leach, 1979; Hagni, 1983; Long and others, 1986).

SALINITY-TEMPERATURE RELATIONSHIPS

No clearly defined relationship is apparent between homogenization and final ice-melting temperatures obtained from individual fluid inclusions (fig. 9). However, the scatter plot for ARK-DW does suggest the presence of a population of higher temperature and lower salinity fluid inclusions hosted by zone 3 dolomite (Th between 240° and 280°C and Tm between –18° and –5.4°C). Fluid inclusions that compose this population form the apparent high-temperature mode at 3.6 km from the Bonneterre Formation in ARK-DW (fig. 5).

Of particular interest shown in figure 9 is the apparent linear array of Th plotted against Tm for samples of zone 3 dolomite-hosted fluid inclusions from samples from the NMTW. This array reflects a large variation in Th values relative to less variable Tm values and is consistent with fluid inclusions that have experienced post-trapping stretching or thermal reequilibration. Considering the evidence for igneous activity in the vicinity of the NMTW, a post-trapping thermal event could account for the elevated Th values observed in the NMTW and possibly in the ARK-DW drill holes.

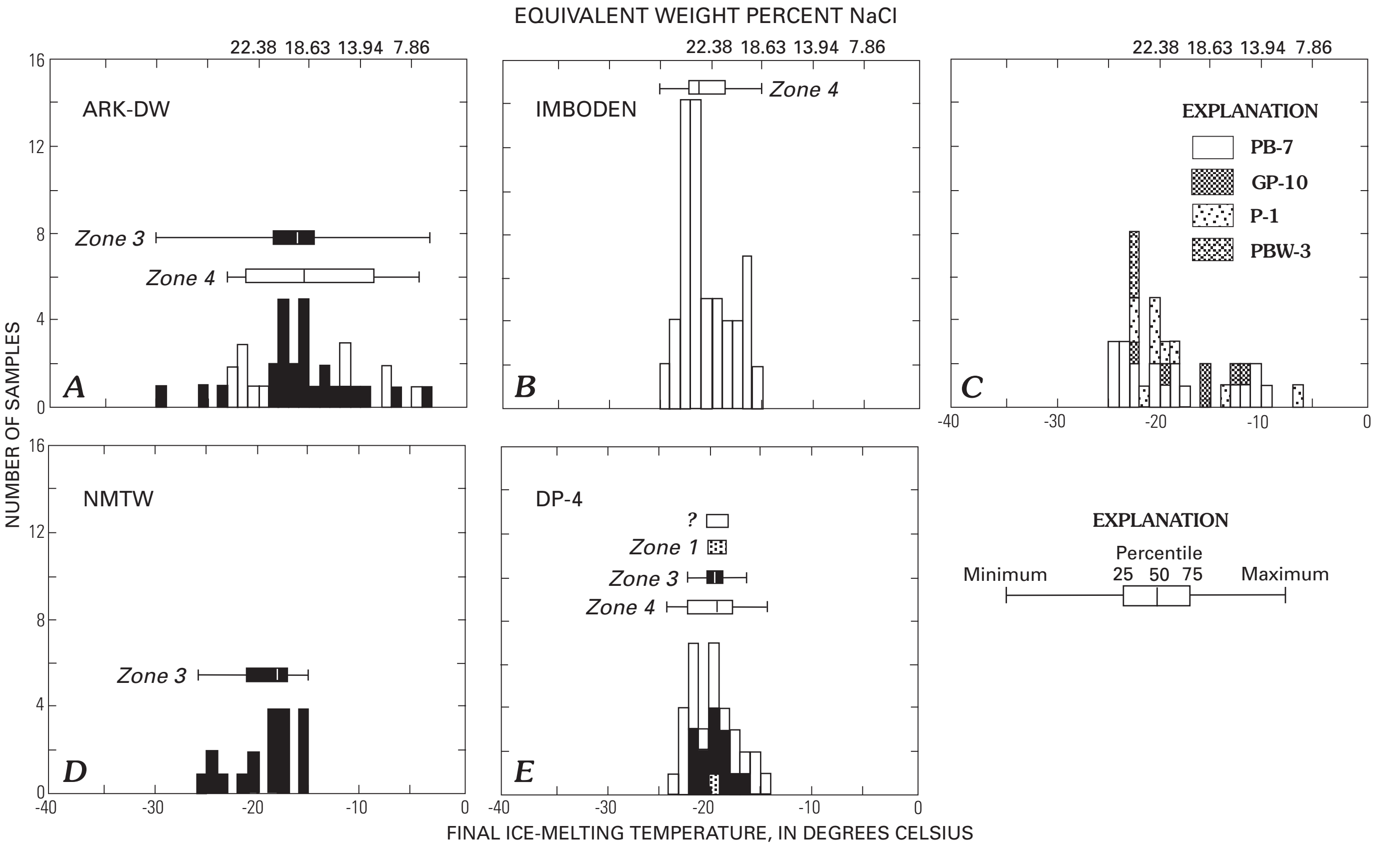

Figure 8. Histogram plots of final ice-melting temperature (Tm). *A*, *B*, Ozark dome; *C*, *D*, Reelfoot rift; *E*, Nashville dome.

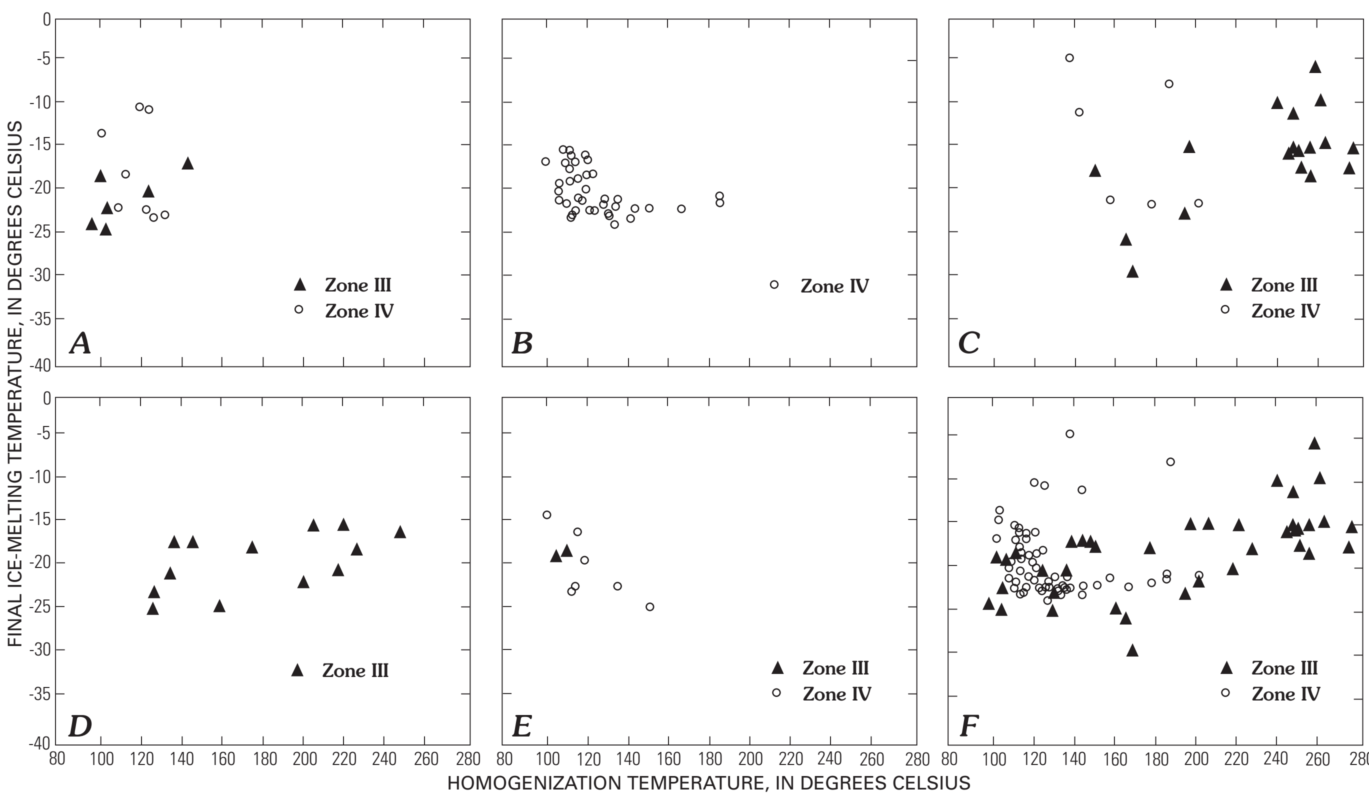

Figure 9. Final ice-melting temperature (Tm) plotted against homogenization temperature (Th) for fluid inclusion data of zone 3 and zone 4 in dolomite from the Ozark dome (*A*, *B*), Reelfoot rift (*C*, *D*), Nashville dome (*E*), and ALL DATA (*F*). *A*, PB-7, GP-10, P-1, PBW-3.

DISCUSSION

The CL microstratigraphy developed for sparry dolomite in southeast Missouri provides a means to correlate sparry dolomite outside the ore districts. However, in the absence of independent age constraints on the sparry dolomite cement, this comparison requires two important assumptions.

First, we assume that the CL zones in our samples are the same zones present in sparry dolomite from the Ozark region. Identification of a CL zone can be subjective, particularly if the entire microstratigraphy is not present or if one or more zones are poorly developed. Even in the Viburnum Trend, where the Ozark CL microstratigraphy was first recognized, samples of sparry dolomite with poorly developed CL zones are common. In most of our samples from the Reelfoot rift complex, the observed CL microstratigraphy was similar to that of the Viburnum Trend but the zones were typically thinner and less complex than those in the Viburnum Trend. For many samples, only two or three zones could be identified with confidence. In addition, the CL zone identified as zone 3 in our samples was generally thinner and contained fewer subbands relative to typical zone 3 dolomite in the Viburnum Trend. We suspect that the less well developed CL zones in the samples from the Reelfoot rift complex may reflect the small size of the dolomite crystals obtained from acid digestion of the carbonate rocks. Nevertheless, we believe that the CL zones in the Reelfoot rift samples are *sufficiently similar* to the Viburnum Trend CL microstratigraphy to propose that they were deposited from a common brine.

Secondly, we assume that the correlative CL zones, whether in samples from the Reelfoot rift or the Ozark region, reflect the broadly contemporaneous precipitation of sparry dolomite. In view of the strong evidence for an interconnected hydrothermal system for the MVT deposits and associated sparry dolomite in the Ozark region, we believe this to be a valid assumption. In addition, many lines of evidence indicate that a MVT fluid migration out of the Reelfoot rift is consistent with our assumption.

Based on the CL microstratigraphy, we suggest that the fluid inclusions in sparry dolomite from the Reelfoot rift complex provide samples of the MVT brines in a portion of what may have been the source of the hot brines that affected much of the Ozark region. The source basin probably included the combined Arkoma and Black Warrior foredeeps together with the thick Paleozoic sedimentary fill in the Reelfoot rift complex, as first suggested by Farr (1989a, 1989b). The results of this study are consistent with the suggestion that the Reelfoot rift zone was an important pathway for the migration of MVT brines into the Southeast Missouri lead districts (Brecke, 1979; Farr and Land, 1985; Farr, 1989a, 1989b; Erickson and others, 1988; Viets and Leach, 1988; Goldhaber and Mosier, 1989; Diehl and others, 1991; Viets and Leach, 1990). However, new lead isotope studies in the region (Goldhaber and others, 1995) show that the lead in the main-stage ores in the Southeast Missouri ore districts contain lead isotope values inconsistent with derivation from the Reelfoot rift. To account for the lead isotope values in the main-stage ores in southeast Missouri, Goldhaber and others (1995) postulated that lead was leached from source rocks in the Ozark region. Our results also suggest that the hydrothermal system responsible for the Ozark MVT districts may have extended onto the western flank of the Nashville dome. This possible extension of the Ozark hydrothermal system suggests the potential for undiscovered MVT resources along the flanks of the Reelfoot rift complex and along the western flank of the Nashville dome.

IMPLICATIONS FOR MIGRATION OF MVT BRINES

Cathodoluminescent microstratigraphy investigations of sparry dolomite from the ARK-DW and NMTW drill holes in the Reelfoot rift show that zone 3 dolomite is most abundant in the Bonneterre Formation. Presumably the Bonneterre Formation was hydrologically connected to the underlying Lamotte Sandstone. Therefore, the lowermost Paleozoic rocks may have been the dominant pathway for migration of brines that deposited zone 3 dolomite in the Reelfoot rift complex and main-stage ores in southeast Missouri. Zone 4 dolomite was not observed in samples from the Bonneterre Formation, either in ARK-DW or NMTW drill holes. However, zone 4 dolomite was deposited in host rocks overlying the Bonneterre Formation in the ARK-DW drill hole. We suggest two possibilities to account for the lack of zone 4 dolomite in samples from the Bonneterre Formation: (1) the brines were undersaturated with respect to dolomite in the lower carbonate section during zone 4 time; therefore, no zone 4 dolomite was deposited in these rocks; (2) at the time of precipitation of zone 4 dolomite, brine migration was mainly through aquifers at higher stratigraphic levels. Zone 4 dolomite is broadly time equivalent to late-stage ores in southeast Missouri and main-stage ores in other Ozark MVT districts. This broad time equivalence is consistent with that of Viets and Leach (1990), who suggested that main-stage ore in the Viburnum Trend was precipitated from a fluid component that interacted with a sandstone aquifer. Shifting fluid migration to higher stratigraphic position in zone 4 time would possibly limit interaction with the basal sandstone in the rift, and is consistent with the lower potassium content in late cubic-stage galena ores of the Viburnum Trend and other MVT districts (Viets and Leach, 1990). If brine migration did shift to higher stratigraphic levels during zone 4 time, the shift could reflect tectonic or structural controls on fluid migration. For example, reactivation and uplift of preexisting basement faults may have forced fluid flow to higher stratigraphic levels in zone 4 time.

THERMAL REGIME IN THE REELFOOT RIFT

Conodont CAI data suggest a minimum paleothermal gradient of about 30°C/km for conodonts between 0.91 and 2.6 km and a minimum temperature of about 150°C at 2.6 km in the ARK-DW drill hole. Our Th data (uncorrected for pressure) for zone 4 fluids are about 135°–205°C at depths between 1.08 and 2.9 km. If the conodonts and Th data for fluid inclusions in zone 4 dolomite record the same thermal regime, then the homogenization temperatures are about 40°–50°C hotter than indicated from CAI. Pressure corrections to the Th data could increase this difference by as much as 30°–50°C.

Homogenization temperatures (uncorrected for pressure) for fluid inclusions in zone 3 dolomite in the ARK-DW at drill hole depths of 3.62 and 3.66 km are between 150° and 280°C, with possible modes at about 190° and 255°C (fig. 5). At estimated maximum burial depths of about 5.3–6.3 km (see previous discussion) in the late Paleozoic, a 30°C/km (25°C ambient surface temperature) geothermal gradient yields minimum temperatures of 184°–214°C. Thus, it appears that zone 3 fluids were hotter than obtainable by a 30°C/km gradient, indicated from conodont CAI in the overlying rocks.

The conodont CAI data and the Th data provide independent estimates for *minimum temperatures* experienced by the samples from the Reelfoot rift. Homogenization temperatures are on the order of 30°–50°C higher than estimates from the conodont data. If pressure corrections are considered for the Th data, the separation in temperatures could be several tens of degrees greater. The most reasonable interpretation of this difference is that the fluid inclusions are recording a transient but short-lived thermal event on the order of 1 m.y. or less. However, it is possible that some of the fluid inclusions may have decrepitated or leaked; however, we did not observe petrographic evidence of this in our samples.

One of the most significant findings in this study is the anomalously high Th values recorded in the Reelfoot rift. For example, Th values in the deepest part of the ARK-DW hole (present depth of 3.66 km) are in the range of 150°–280°C; most of the data are in the range 220°–260°C. Based on estimates of the stratigraphic overburden in late Paleozoic time (5–6 km), possible pressure corrections to these data would yield corrected temperatures of about 50°–60°C higher. For a 60°C pressure correction, the actual temperatures achieved in the deepest part of ARK-DW would be in the range 210°–340°C. This range would be equivalent to burial geothermal gradients of approximately 35°–60°C/km. Assuming that the fluid inclusions have not leaked, the high temperatures reflect either temperatures of advecting hydrothermal brines or thermally reequilibrated fluid inclusions in response to higher basement-derived, conductive geothermal gradient. In either case, the fluid inclusion data point to a thermal event in the central Reelfoot rift where temperatures of about 300°C were achieved in the Bonneterre Formation.

SOURCE OF THE BRINES

The source of the highly saline fluids that formed the sparry dolomite and the MVT deposits in the Ozark region remains problematic. However, the general opinion is that the high salinity levels of most subsurface sedimentary brines are probably related to dissolution of evaporites and (or) subaerially produced brines (bitterns) associated with evaporation of seawater. (See Carpenter, 1978; Land and Prezbindowski, 1981; Hanor, 1987, among others.) Although the few drill holes in the Reelfoot rift have never encountered bedded evaporites, McKeown and others (1990) reported as much as 5 percent intergranular barite and anhydrite in part of the ARK-DW drill hole; about 1 percent gypsum is present in the ARK-DW drill hole. Denison (1984) also reported anhydrite in the crystalline basement in the ARK-DW drill hole. Furthermore, sulfur isotope studies of Paleozoic rocks in the Pascola arch and vicinity are consistent with sulfur derived from reduction of evaporite sulfate by organic matter (Goldhaber and Mosier, 1989). Continental rift basins commonly contain evaporite sequences (Ziegler, 1988; Hardie and others, 1978). Therefore, a reasonable hypothesis is that evaporites accumulated in the Reelfoot rift during late Proterozoic and Early Cambrian rifting could have provided a source for the highly saline fluids that deposited the sparry dolomite.

VARIATION IN TEMPERATURE AND SALINITY

The scatter plots for temperature and salinity for our samples (fig. 9) are similar to those of other fluid inclusion studies throughout the region that indicate independent variations in temperature and salinity (Leach and others, 1975; Leach, 1979; Roedder, 1977; Long and others, 1986; Rowan and Leach, 1989). For samples from the Reelfoot rift, the range in fluid inclusion data is exceptionally large. Some variation in the Th data can be attributed to undetected necking of fluid inclusions (Leach and Rowan, 1993); however, the large range of Th values observed for samples from the Reelfoot rift is unlikely attributable to necking alone. Variability related to recrystallization of the sparry dolomite or leakage of the fluid inclusions was not important based on our petrographic observations. Changes in fluid pressure during crystal growth can account for some variation in Th values. However, at any given site during growth of the dolomite crystal, the possible variations in pressure are expected to be too small to account for significant variability in the Th values. The observed range in Th and Tm values more likely reflects changes in the salinity and temperature of the hydrothermal fluids, or in the case of the Reelfoot rift samples, post-trapping thermal stretching or reequilibrium of the fluid inclusions.

CHANGES IN TEMPERATURE AND SALINITY RELATED TO FLUID MIXING

It is tempting to invoke fluid mixing *at each site* of mineral deposition to explain the large variation observed in temperature and salinity of the fluid inclusions. Many studies call upon fluid mixing to account for ore deposition in the Viburnum Trend district (Rowan and Leach, 1989; Viets and Leach, 1990; Burstein and others, 1991; Shelton and others, 1991; Shelton, Bauer, and Gregg, 1992; Plumlee and others, 1995) and in other MVT districts such as East Tennessee (Taylor and others, 1983) and Sweetwater district (Zimmerman and Kesler, 1981). In addition, a variety of fluid mixing models are proposed for sparry dolomite precipitation. Rowan and Leach (1989) suggested that the wide variation in salinity and temperature of sparry dolomite in the Viburnum Trend reflects the presence of more than one fluid during ore deposition and that fluid mixing probably occurred. In a recent study of sparry dolomite from the Ozark region (Shelton, Bauer, and Gregg, 1992), fluid mixing was invoked to explain the variance in homogenization–final melting temperatures.

An alternative to *local*, site-specific, fluid mixing to explain the variation in salinity is the migration of pulses of brines whose temperature and salinity reflect large-scale processes *within* the source basin of the brines. Sedimentary basins typically contain fluids that differ significantly in composition and salinity. (See Hanor, 1979, 1987; Carpenter, 1978, among others.) As Hanor (1987, p. 54) pointed out, these variations probably represent blends of various end member fluids which include bitterns, brines produced through dissolution of evaporites, and influxes of meteoric water. Thus, fluid mixing within the Ouachita basin complex would have produced a range of fluid inclusion salinities in sparry dolomite in the Reelfoot rift and throughout the Ozark dome and western flank of the Nashville dome. The expulsion of fluids from the Ouachita basin complex, containing a range of fluid salinities, would likely result in transient changes in fluid salinity at any given location along the brine's flow path. Fluid-rock reactions as well as additional fluid mixing during brine migration would further add to the variability. We believe that much of the variation in salinity in sparry dolomite observed for the Ozark region can be related to inherent variations in salinity within the Ouachita basin complex produced by fluid mixing within the basin. In this scenario, fluid inclusions in sparry dolomite in the Ozark region and western flank of the Nashville dome record this variation in temperature and salinity through time of fluid migration from the source basin.

The large range in fluid inclusion homogenization temperatures, particularly in samples from the Reelfoot rift, may in part reflect real variations in trapping temperatures. The temperature of the mineralizing fluid at a site where sparry dolomite is precipitating must be related to the fluid migration pathway, starting temperature of the fluid in the source basin, rate of fluid migration, local thermal regime at the depositional site, and amount of thermal insulation provided by the overlying rocks. Fluid migrating through the Reelfoot rift complex in late Paleozoic time would likely experience considerable transient temperature variations. During the closing stages of Ouachita orogeny in the late Paleozoic, compression taking place in the Reelfoot rift complex probably reactivated basement faults that would disturb and modify fluid migration pathways. Ouachita compression also produced uplift in arches (such as Pascola arch) and domes (such as Nashville and Ozark), which could also cause transient changes in the fluid pathways and flow rates. The Paleozoic sedimentary fill in the Reelfoot rift varies as much as 4 km (Nelson and Zhang, 1991), and fluids migrating through this variable sedimentary fill could vary as much as 120°C for a 30°C/km basement-controlled geothermal gradient. In addition, the drive for the regional hydrothermal system was likely topographic head in the uplifted Ouachita foldbelt; therefore, changes in topographic head in the Ouachita foldbelt would also influence fluid-flow rates and pathways.

POST-TRAPPING THERMAL STRETCHING OR REEQUILIBRATION

The fluid inclusion data for sparry dolomite in the Ozark dome are similar to data for the MVT ore deposits. No evidence exists for igneous activity or other thermal events near the ore deposits of the Ozark dome after ore deposition that could have disturbed the Th data. However, the situation in the Reelfoot rift is quite different. In the Reelfoot rift, the fluid inclusion data show a large range in values, and intrusive activity is known to have been coeval with or to postdate the inferred time of sparry dolomite precipitation. Some of this variability may be related to the presence of more than one fluid, especially for samples from the ARK-DW drill hole. However, the extreme range of Th relative to much more restricted range in Tm, especially for NMTW, is suggestive of stretching or reequilibration of the fluid inclusions from a post-trapping thermal event.

Known igneous activity in the Reelfoot rift complex includes emplacement of Late Pennsylvanian to Permian age alkalic dikes and sills in the vicinity of Hicks dome in the southern Illinois fluorspar district and in the vicinity of the Pascola arch. In addition, an inferred igneous intrusion lies about 30 km east of the ARK-DW drill hole. Elevated thermal conditions, related to the known igneous activity, possibly were coeval with or followed formation of the sparry dolomite. Previously trapped fluid inclusions would likely have expanded or stretched to achieve new fluid densities approaching values more consistent with the thermal conditions imposed by the elevated thermal environment. If stretching of fluid inclusions did occur, the reported Th values would more closely reflect the imposed thermal regime, therefore still providing evidence of paleothermal conditions in the Reelfoot rift.

CONCLUSIONS

The fluid inclusion, CL, and CAI investigations must be considered as a reconnaissance study of the involvement of the Reelfoot rift complex in the Ozark MVT hydrothermal system. Our study was of only two drill holes in the Reelfoot rift and one along the Nashville dome. Certainly more work is needed to confirm our observations and support our conclusions. Nevertheless, the following conclusions appear to be reasonable:

1. The CL microstratigraphy of sparry dolomite cement in the Reelfoot rift complex is similar to that observed in the Ozark region. Although the CL microstratigraphy in the Reelfoot rift complex is simpler and less well developed than in the Ozark region, the two are sufficiently similar to suggest deposition of sparry dolomite from a common brine.

2. Fluid inclusion and CL studies suggest that the hot brines responsible for widespread formation of MVT mineralization in the Ozark region were also present in the Reelfoot rift complex in the late Paleozoic. This interpretation is consistent with other studies that suggest the Reelfoot rift complex as an important pathway for migration of MVT brines into the Southeast Missouri lead districts.

3. The Ozark hydrothermal system may have extended into the western flank of the Nashville dome. This extension is suggested by the presence of sparry dolomite cement in drill hole DP-4, in which CL microstratigraphy and fluid inclusion homogenization and salinities are similar to those in the Ozark region. The CL zoning in samples from the western Nashville dome are distinctly different from those reported from sparry dolomite along the crest of the Nashville dome near the Central Tennessee MVT district.

4. Zone 3 dolomite, temporally related to main-stage ores in southeast Missouri, was observed to be best developed in the Bonneterre Formation and in drill holes ARK-DW and NMTW in the Reelfoot rift complex. Zone 4 dolomite is temporally related to deposition of late-stage ores in southeast Missouri and main-stage ores in the other Ozark MVT districts. Zone 4 dolomite was observed only in post-Bonneterre Formation rocks in ARK-DW. Possible reasons for the absence of zone 4 dolomite in the lower Bonneterre Formation in the Reelfoot rift are: (1) Zone 4 brines did not precipitate dolomite in the lowermost section because the fluids were at or below dolomite saturation in these rocks; or (2) fluid flow shifted to higher stratigraphic levels from zones 3 to 4 time.

5. Conodont CAI data from Lower Ordovician rocks in the Reelfoot rift from the ARK-DW drill hole are consistent with a minimum paleothermal gradient of about 30°C/km. Fluid inclusion homogenization temperatures (uncorrected for pressure) obtained for fluid inclusions hosted in sparry dolomite in the ARK-DW drill hole are similar (but about 30°–50°C higher) relative to temperatures estimated from conodont CAI. Pressure corrections to the fluid inclusion homogenization temperatures could extend the difference by as much as an additional 30°–50°C. The difference in temperatures from conodont CAI and fluid inclusions is probably due to the fact that the CAI values are a time-dependent indicator; a short-lived thermal event of less than 1 m.y. in the rift might be undetected in the conodont CAI. The fluid inclusions may record the passage of transient but higher temperature fluids or a short-lived thermal event related to igneous activity.

6. CAI values found in the ARK-DW drill hole provide evidence of the amount of post-Lower Ordovician strata eroded before the Cretaceous. For a burial thermal gradient of 30°C/km for at least 1 m.y., about 2.1–3.7 km of Paleozoic strata have been removed. The total amount of post-Lamotte Paleozoic strata present before the pre-Cretaceous erosion could be between 5.3 and 6.3 km. However, if the CAI values are reflecting local thermal effects from advecting hydrothermal fluids or local igneous activity, these estimates may be too large, although there appears to be no downhole perturbation of either the CAI trend or within-sample color value or surface textural variations to indicate these smaller scale, nonburial heating effects.

7. The fluid inclusion homogenization data provide estimates of the minimum temperatures of fluid trapping and (or) burial temperatures for the sparry dolomite. Pressure corrections can be estimated, assuming hydrostatic fluid pressures and estimates of the maximum depth of burial. For the Ozark and Nashville domes, the maximum pressure corrections to the homogenization data probably do not exceed 15°–20°C. In the Reelfoot rift, estimated pressure corrections could be as high as 45°–60°C. Uncertainties related to actual burial depths limit comparisons between locations to broad conclusions. Nevertheless, the data do provide important constraints on the thermal regime in the region in late Paleozoic time.

8. Fluid inclusion homogenization and salinity data for sparry dolomite in the Ozark and Nashville domes are similar to values reported for sphalerite and sparry dolomite from the MVT districts in the Ozark region. Most of the new homogenization temperatures fall between 100° and 140°C; pressure corrections to these data probably do not exceed 15°–20°C. Final ice-melting temperatures are mostly between –10° and –25°C, corresponding to about 15 to greater than 23 equivalent weight percent NaCl salinities.

9. Fluid inclusion homogenization temperatures for samples of sparry dolomite and CAI values in Ordovician rocks in the Reelfoot rift are significantly higher than those for sparry dolomite from the Ozark and Nashville domes. For example, fluid inclusions in zone 4 dolomite from the ARK-DW drill hole in the Reelfoot rift are about 60°C hotter than those in zone 4 dolomite located 50 km distant at Imboden, Ark. Fluid inclusions in zone 3 dolomite in the Reelfoot rift may be more than 100°C hotter than those found in zone 3 dolomite in the Ozark dome. Pressure corrections to the homogenization temperatures could extend these temperature differences by as much as 40°–60°C.

10. In the ARK-DW drill hole, fluid inclusions in zone 4 dolomite have distinctly lower homogenization temperatures relative to fluid inclusions in zone 3 dolomite. The apparent difference in homogenization temperatures between zones 3 and 4 fluid inclusions could be about 50°C. If pressure corrections to the homogenization temperatures, due to the stratigraphic separation between zones 3 and 4 dolomite, are considered, the difference in temperatures could be about 60°C. The difference between the homogenization temperatures for zones 3 and 4 fluid inclusions most likely reflects a real difference in the temperatures of the fluids that formed zones 3 and 4 dolomite.

11. One of the most significant findings in this study is the high fluid inclusion temperatures recorded in sparry dolomite from the Reelfoot rift. Homogenization values in the deepest part of the ARK-DW drill hole (present depth of 3.66 km) are in the range of 150°–280°C; most of the data are in the range 220°–260°C. Applying a 60°C pressure correction, the actual temperatures achieved in the deepest part of ARK-DW could be in the range 210°–340°C. This range would be equivalent to burial geothermal gradients of approximately 35°–60°C/km. The high temperatures reflect either the temperatures of advecting hydrothermal brines or thermally reequilibrated fluid inclusions in response to higher basement-derived, conductive geothermal gradient. In either case, the fluid inclusion data point to a thermal event in the central Reelfoot rift where temperatures of around 300°C were achieved in the Bonneterre Formation.

12. For samples of sparry dolomite at any given location or depth in the Reelfoot rift, the range in homogenization temperatures is rather large. For example, at 3.62 to 3.66 km in ARK-DW, the homogenization temperatures range from 155°–280°C. This large range in homogenization temperatures may be explained by significant but transient changes in temperatures of advecting hydrothermal fluids. Alternatively, the range could be the result of the stretching or reequilibration of the fluid inclusions from a post-trapping thermal event. The possible post-trapping thermal event could be related to the Late Pennsylvanian to Permian intrusive activity known in the Reelfoot rift complex. If stretching of fluid inclusions did occur, the reported Th values would more closely reflect the imposed thermal regime; therefore, they would still provide constraints on the thermal conditions in the Reelfoot rift in late Paleozoic time.

13. High homogenization temperatures and relatively low salinities of many of the fluid inclusions from zone 3 dolomite in ARK-DW from the Bonneterre Formation suggest the presence of a hotter and more dilute fluid component in the Reelfoot rift. Fluid inclusion data from other samples in the study area generally show significant but independent variation between homogenization temperature and salinity. These variations in temperature and salinity may reflect transient variations in fluid flow or fluid mixing within the Ouachita basin complex. However, the salinity-temperature relationship for samples from the NMTW shows significantly greater variation in temperature relative to salinity, suggestive of post-trapping stretching or thermal reequilibration of the fluid inclusions.

REFERENCES CITED

Bass, M.N., and Ferrara, G., 1969, Age of adularia and metamorphism, Ouachita Mountains, Arkansas: American Journal of Science, v. 257, p. 491–498.

Bauer, R.M., and Shelton, K.L., 1989, Fluid inclusion studies of regionally extensive epigenetic dolomites, Bonneterre Dolomite, S.E. Missouri—Evidence of multiple fluids during Pb-Zn ore mineralization: Geological Society of America Abstracts with Programs, v. 21, p. A3.

Bodnar, R.J., 1992, Revised equation and table for freezing-point depressions of H_2O-salt fluid inclusions: PACROFI IV Program and Abstracts, p. 15.

Bodnar, R.J., and Bethke, P.M., 1984, Systematics of stretching of fluid inclusions—I, Fluorite and sphalerite at 1 atmosphere confining pressure: Economic Geology, v. 79, p. 141–161.

Brannon, J.C., Cole, S.C., and Podosek, F.A., 1995, Can all Mississippi Valley–type deposits be radiometrically dated?, *in* Leach, D.L., and Goldhaber, M.B., eds., Extended abstracts: International Field Conference on carbonate-hosted lead-zinc deposits, Society of Economic Geologists, St. Louis, Mo., June 1995, p. 27–29.

Brannon, J.C., Podosek, F.A, and McLimans, R.K., 1992, Alleghenian age of the Upper Mississippi Valley zinc-lead deposit determined by Rb-Sr dating of sphalerite: Nature, v. 356, p. 509–511.

Brecke, E.A., 1979, A hydrothermal system in the Midcontinent Region: Economic Geology, v. 74, p. 1327–1335.

Burruss, R.C., 1987, Diagenetic paleotemperatures from aqueous fluid inclusions—Re-equilibration of inclusions in carbonate cements by burial heating: Mineralogical Magazine, v. 51, p. 477–481.

Burstein, I.B., Shelton, K.L., Hagni, R.D., and Mavorgenes, J.A., 1991, District-wide sulfur isotope systematics of MVT ores in the world-class southeast Missouri Pb-Zn-Cu deposits—Sulfur isotope anomalies indicative of the simultaneous presence of multiple fluids: Geological Society of America Abstracts with Programs, v. 24, p. 414.

Caplan, W.M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkansas: Arkansas Geological Commission Bulletin, v. 20, 124 p.

Carpenter, A.B., 1978, Origin and chemical evolution of brines in sedimentary basins: Oklahoma Geological Survey Circular 79, p. 60–77.

Chesley, J.T., Halliday, A.N., Kyser, T.K., and Spry, P.G., 1994, Direct dating of Mississippi Valley-type mineralization—Use of Sm-Nd in fluorite: Economic Geology, v. 89, p. 1192–1199.

Crone, A.F., McKeown, F.A., Harding, S.T., Hamilton, R.M., Russ, D.P., and Zoback, M.D., 1985, Structure of the New Madrid seismic source zone in southeastern Missouri and northeastern Arkansas: Geology, v. 13, p. 547–550.

Denison, R.E., 1984, Basement rocks in northern Arkansas, *in* Mc Farland, J.D., and Bush, W.V., eds., Contributions to the geology of Arkansas, Volume II: Arkansas Geological Commission Miscellaneous Publication 18–B, p. 33–49.

Desborough, G.A., Zimmerman, R.A., Elrick, M., and Stone, C., 1985, Permian thermal alteration of Carboniferous strata in the Ouachita region and Arkansas River Valley, Arkansas: Geological Society of America Abstracts with Programs, v. 17, p. 155.

Diehl, S.F., Goldhaber, M.B., Taylor, C.D., Swolfs, H.S., and Gent, C.A., 1991, Microstructures in the Cambrian Bonneterre Formation, Lamotte Sandstone, and basal clastic rocks of Southeast Missouri and Northeast Arkansas—Implications of regional sulfide occurrence in stylolites and extensional veinlets for ore genesis, Chapter A *in* Thorman, C.H., ed., Application of structural geology to mineral and energy resources of the Central and Western United States: U.S. Geological Survey Bulletin 2012, p. A1–A13.

Duffin, M.E., Lee, M., Klein, G., and Hay, R.L., 1989, Potassic diagenesis of Cambrian sandstones and Precambrian granitic basement in UPH-3 deep hole, Upper Mississippi Valley, U.S.A.: Journal of Sedimentary Petrology, v. 59, no. 5, p. 848–861.

Epstein, A.G., Epstein, J.B., and Harris, L.D., 1977, Conodont color alteration—An index to organic metamorphism: U.S. Geological Survey Professional Paper 995, 27 p.

Erickson, R.L., Mosier, E.L., Odland, S.K., and Erickson, M.S., 1981, A favorable belt for possible mineral discovery in subsurface Cambrian rocks in southern Missouri: Economic Geology, v. 76, p. 921–933.

Erickson, R.L., Chazin, B., Erickson, M.S., Mosier, E.L., and Whitney, H., 1988, Tectonic and stratigraphic control of regional subsurface geochemical patterns, midcontinent, U.S.A., *in* Kisvarsanyi, G., and Grant, S.K., eds., Proceedings of Tectonic Control of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems: Rolla, Mo., University of Missouri, Rolla Press, p. 435–446.

Ervin, C.P., and McGinnis, L.D., 1975, Reelfoot rift—Reactivated precursor to the Mississippi Embayment: Geological Society of America Bulletin, v. 86, p. 1287–1295.

Farr, M. R., 1989a, Regional isotopic variation in Bonneterre Formation dolomite cements: Implications for brine migration pathways and sources [abs.], *in* Gregg, J. M., and Hagni, R. D., eds., Symposium on the Bonneterre Formation (Cambrian), Southeastern Missouri: Rolla, Mo., University of Missouri-Rolla, p. 8.

———1989b, Compositional zoning characteristics of late dolomite cement in the Cambrian Bonneterre Formation, Missouri; Implications for parent fluid migration pathways: Society of Economic Paleontologists and Mineralogists, Carbonates and Evaporites, v. 4, no. 2, p. 177–194.

Farr, M.R., and Land, L.S., 1985, Cathodoluminescent zoning as a guide to regional paleohydrology of mineralizing brines in southern Missouri: American Association of Petroleum Geologists Annual Midyear Meeting Abstracts, v. ii, p. 29.

Frank, M.H., and Lohmann, K.C., 1986, Textural and chemical alteration of dolomite—Interaction of mineralizing fluids and a host rock in a Mississippi Valley-type deposit, Bonneterre Formation, Viburnum Trend, *in* Hagni, R.D., ed., Process mineralogy VI: Warrendale, Pa., The Metallurgical Society, p. 103–117.

Gerdemann, P.E., and Meyers, H.E., 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the Southeast Missouri lead district: Economic Geology, v. 67, p. 426–433.

Goldhaber, M.B., Church, S.E., Doe, B.R., Aleinikoff, J.N., Brannon, J.C., Podosek, F.A., Mosier, E.L., Taylor, C.D., and Gent, C.A., 1995, Lead- and sulfur-isotope investigation of Paleozoic sedimentary rocks from the southern midcontinent of the United States: Economic Geology, v. 90, p. 1875–1910.

Goldhaber, M.B., and Mosier, E.L., 1989, Sulfur sources for southeast Missouri MVT ores—Implications for ore genesis, *in* Pratt, W.P., and Goldhaber, M.B., eds., U.S. Geological Survey-Missouri Geological Survey Symposium—Mineral Resource Potential of the Midcontinent; Program and Abstracts: U.S. Geological Survey Circular 1043, p. 8–9.

Goldhaber, M.B., Potter, C.J., and Taylor, C., 1992, Constraints on Reelfoot rift evolution from a reflection seismic profile in the Northern rift: Seismological Research Letters, v. 63, no. 3, p. 233–241.

Goldhaber, M.B., and Stanton, M.R., 1987, Experimental formation of marcasite at 150–200°C; Implications for carbonate-hosted Pb-Zn deposits: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 678.

Goldstein, R.H., 1986, Re-equilibration of fluid inclusions in low-temperature calcium-carbonate cement: Geology, v. 14, p. 792–795.

Goldstein, R.H., and Reynolds, T.J., 1994, Systematics of fluid inclusions in diagenetic minerals: Society for Sedimentary Geology Short Course 31, 199 p.

Gorody, A.W., 1980, The Lower Ordovician Mascot Formation, upper Knox Group, in north central Tennessee; Part I, Paleoenvironmental history; Part II, Dolomitization and paleohydraulic history: Houston, Texas, Rice University Ph. D. dissertation, 263 p.

Gregg, J.M., 1985, Regional epigenetic dolomitization in the Bonneterre Dolomite (Cambrian), southeastern Missouri: Geology, v. 13, p. 503–506.

Hagni, R.D., 1983, Minor elements in Mississippi Valley-type ore deposits, *in* Shanks, W.C., ed., Cameron volume on unconventional mineral deposits: New York, Society of Economic Geology and Society of Mining Engineers, AIME, p. 44–88.

Hamilton, R.M., and McKeown, F.A., 1988, Structure of the Blytheville arch in the New Madrid seismic zone: Seismological Research Letters, v. 59, no. 4, p. 117–121.

Hanor, J.S., 1979, The sedimentary genesis of hydrothermal fluids, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, Wiley-Interscience, p. 137–142.

———1987, Origin and migration of subsurface sedimentary brines; lecture notes for Short Course No. 21: Society of Ecnomic Paleontologists and Mineralogists, 247 p.

Hardie, L.A., Smoot, J.P., and Eugster, H.P., 1978, Saline lakes and their deposits—A sedimentological approach: Special Publication of the Association of Sedimentology, v. 2, p. 741.

Harris, A.G., 1979, Conodont color alteration, an organo-mineral metamorphic index, and its application to Appalachian basin geology: SEPM Special Publication 26, p. 316.

Hay, R.L., Lee, M., Kolata, D.R., Matthews, J.C., and Morton, J.P., 1988, Episodic potassic diagenesis of Ordovician tuffs in the Mississippi Valley area: Geology, v. 16, p. 743–747.

Hildenbrand, T.G., 1985, Rift structure of the northern Mississippi Embayment from the analysis of gravity and magnetic data: Journal of Geophysical Research, v. 90, p. 12607–12622.

Hildenbrand, T.G., Kane, M.F., and Stauder, W., 1977, Magnetic and gravity anomalies in the northern Mississippi Embayment and their spatial relation to seismicity: U.S. Geological Survey Miscellaneous Field Studies Map MF-914, scale 1:1,000,000.

Hofstra, A.H., Leach, D.L., Landis, G.P., Viets, J.G., Rowan, E.L., and Plumlee, G.S., 1989, Fluid inclusion gas geochemistry as a monitor of ore depositional processes in Mississippi Valley-type deposits in the Ozark region, *in* Pratt, W.P., and Goldhaber, M.B., eds., U.S. Geological Survey–Missouri Geological Survey Symposium—Mineral Resource Potential of the Midcontinent; Program and Abstracts: U.S. Geological Survey Circular 1043, p. 1112.

Horrall, K.B., Hagni, R.D., and Kisvarsanyi, G., 1993, Mafic and ultramafic plutons associated with the New Madrid Rift—A possible major source for the copper-cobalt-nickel mineralization of Southeast Missouri: Economic Geology, v. 88, p. 328–343.

Howe, J.R., 1985, Tectonics, sedimentation, and hydrocarbon potential of the Reelfoot Aulacogen: Norman, Okla., University of Oklahoma M.S. thesis, 109 p.

Howe, J.R., and Thompson, T.L., 1984, Tectonics, sedimentation, and hydrocarbon potential of the Reelfoot rift: Oil and Gas Journal, p. 179–190.

Kane, M.F., Hildenbrand, T.G., and Hendricks, J.D., 1981, A model for the tectonic evolution of the Mississippi Embayment and its contemporary seismicity: Geology, v. 9, p. 563–567.

Kolata, D.R., and Nelson, W.J., 1991, Tectonic history of the Illinois basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 263–285.

Kopp, O.C., Ebers, M.L., Cobb, L.B., Crattie, T.B., Ferguson, T.L., Larsen, R.M., Potosky, R.A., and Steinberg, R.T., 1986, Application of cathodoluminescence microscopy to the study of gangue carbonates in Mississippi Valley-Type deposits in Tennessee—The search for a "Tennessee Trend," *in* Hagni, R.D., ed., Process mineralogy VI: Warrendale, Pa., The Metallurgical Society, p. 69–87.

Land, L.S., and Prezbindowski, D.R., 1981, The origin and evolution of saline formation water, Lower Cretaceous carbonates, south-central Texas, U.S.A.: Journal of Hydrology, v. 54, p. 51–74.

Leach, D.L., 1979, Temperature and salinity of the fluids responsible for minor occurrences of sphalerite in the Ozark region of Missouri: Economic Geology, v. 74, p. 931–937.

Leach, D.L., Nelson, R.C., and Williams, D., 1975, Fluid inclusion studies in the Northern Arkansas zinc district: Economic Geology, v. 70, p. 1084–1091.

Leach, D.L., Plumlee, G.S., Hofstra, A.H., Landis, G.P., Rowan, E.L., and Viets, J.B., 1991, Origin of late dolomite cement by CO_2-saturated deep basin brines—Evidence from the Ozark region, U.S.A.: Geology, v. 19, p. 348–351.

Leach, D.L., and Rowan, E.L., 1986, Genetic link between Ouachita foldbelt tectonism and the Mississippi Valley-type lead zinc deposits of the Ozarks: Geology, v. 14, p. 931–935.

———1993, Discussion on "fluid-inclusion studies of regionally extensive epigenetic dolomites, Bonneterre Dolomite (Cambrian), southeast Missouri: Evidence of multiple fluids during dolomitization and lead-zinc mineralization" by Shelton and others, 1992a: Geological Society of America Bulletin, v. 105, p. 968–978.

Lewis, R.D., 1987, Alnoite intrusives associated with Permian rifting in the New Madrid seismic complex: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 745.

Long, K.R., Kelly, W.C., Ohle, E.L., and Lohmann, K.C., 1986, Ground preparation and zinc mineralization in bedded and breccia ores of the Monte Cristo mine, North Arkansas: Economic Geology, v. 81, p. 809–830.

McKeown, F.A., Hamilton, R.M., Diehl, S.F., and Glick, E.E., 1990, Diapiric origin of the Blytheville and Pascola arches in the Reelfoot rift, east-central United States—Relation to New Madrid seismicity: Geology, v. 18, p. 1158–1162.

Nelson, K.D., Lillie, R.J., deVoogd, B., Brewer, J.A., Oliver, J.E., Kaufman, S., Brown, L., and Viele, G.W., 1982, COCORP seismic reflections profiling in the Ouachita Mountains of western Arkansas—Geometry and geologic interpretations: Tectonics, v. 1, p. 413–430.

Nelson, K.D., and Zhang, J., 1991, A COCORP deep reflection profile across the buried Reelfoot rift, south-central United States: Tectonophysics, v. 197, p. 271–293.

Palmer, J.R., and Hayes, T.S., 1989, Late Cambrian lithofacies and their control on the Mississippi Valley–type mineralizing system in the Ozark region, *in* Schindler, K.S., ed., U.S. Geological Survey Research on Mineral Resources–1989 Program and Abstracts: United States Geological Survey Circular 1035, p. 51–53.

Pan, H., Symons, D.T.A., and Sangster, D.F., 1990, Paleomagnetism of the Mississippi Valley-type ores and host rocks in the Northern Arkansas and Tri-State districts: Canadian Journal of Earth Sciences, v. 27, p. 923–931.

Plumlee, G.S., Leach, D.L., Hofstra, A.H., Landis, G.P., Rowan, E.L., and Viets, J.B., 1995, Chemical reaction path modeling of ore deposition in Mississippi Valley-type Pb-Zn deposits of the Ozark region, U.S. midcontinent: Economic Geology, v. 89, p. 1361–1383.

Posey, H.H., Stein, H.J., Fullagar, P.D., and Kish, S.A., 1983, Rb-Sr isotopic analyses of Upper Cambrian glauconites, southern Missouri—Implications for movement of Mississippi Valley–type ore fluids in the Ozark region, *in* Kisvarsanyi, G., and others, eds., Proceedings of International Conference on Mississippi Valley-Type Lead-Zinc Deposits: Rolla, Mo., University of Missouri, p. 166–173.

Prezbindowski, D.R., and Larese, R.E., 1987, Experimental stretching of fluid inclusions in calcite—Implications for diagenetic studies: Geology, v. 15, p. 333–336.

Rejebian, V.A., Harris, A.G., and Huebner, J.S., 1987, Conodont color and textural alteration—An index to regional metamorphism, contact metamorphism, and hydrothermal alteration: Geological Society of America Bulletin, v. 99, p. 471–479.

Roedder, E., 1967, Environment of deposition of stratiform (Mississippi Valley-type) ore deposits, from studies of fluid inclusions: Economic Geology Monograph 3, p. 349–362.

———1977, Fluid inclusion studies of ore deposits in the Viburnum Trend, southeast Missouri: Economic Geology, v. 72, p. 513–528.

———1984, Fluid inclusions: Reviews in Mineralogy, Volume 12: Mineralogical Society of America, 644 p.

Rothbard, D.R., 1983, Diagenetic history of the Lamotte Sandstone, Southeast Missouri, *in* Kisvarsanyi, G., and others, eds., Proceedings of the International Conference on Mississippi Valley-type lead-zinc deposits: Rolla, Mo., University of Missouri-Rolla Press, p. 385–392.

Rowan, E.L., 1986, Cathodoluminescent zonation in hydrothermal dolomite cements—Relationship to Mississippi Valley-type Pb-Zn mineralization in southern Missouri and northern Arkansas, *in* Hagni, R.D., ed., Process mineralogy VI: Warrendale, Pa., Metallurgical Society, p. 69–87.

Rowan, E.L., and Leach, D.L., 1989, Constraints from fluid inclusions on sulfide precipitation mechanisms and ore fluid migration in the Viburnum Trend Lead District, Missouri: Economic Geology, v. 84, p. 1948–1965.

Schwalb, H.R., 1982, Paleozoic geology of the New Madrid Area, *in* New Madrid seismotectonic study: Illinois State Geological Survey, NUREG/CR-2909, p. 77–79.

Shelton, K.L., Bauer, R.M., and Gregg, J.M., 1992, Fluid inclusion studies of regionally extensive epigenetic dolomites, Bonneterre Formation (Cambrian), southeast Missouri—Evidence of multiple fluids during dolomitization and lead-zinc mineralization: Geological Society of America Bulletin, v. 104, p. 675–683.

Shelton, K.L., Burstein, I.B., and Hagni, R.D., 1991, Sulfur isotope geochemistry of detailed mineral paragenesis, Viburnum Trend MVT deposits, S.E. Missouri—Evidence of multiple basement and basinal sulfur sources: Geological Society of Canada Programs with Abstracts, v. 16, p. A133.

Shelton, K.L., Haeussler, G., and Burstein, I.B., 1992, Dolomitization and fluid interaction in the Reelfoot rift, southeastern Missouri—Geochemical and petrographic studies: Geological Society of America Abstracts with Programs, v. 94, p. A57.

Shelton, K.L., Reader, J.M., Ross, L.M., Viele, G.W., and Siedeman, D.E., 1986, Ba-rich adularia from the Ouachita Mountains, Arkansas—Implications for a post-collisional hydrothermal system: American Mineralogy, v. 71, p. 916–923.

Snyder, F.G., and Gerdemann, P.E., 1968, Geology of the southeast Missouri lead district, *in* Ridge, J.D., ed., Ore deposits of the United States (Graton-Sales volume): New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 326–358.

Stearns, R.G., and Marcher, M.V., 1962, Late Cretaceous and subsequent structural development of the northern Mississippi Embayment area: Geological Society of America Bulletin, v. 73, p. 1387–1394.

Stein, H.J., and Kish, S.A., 1985, The timing of ore formation in Southeast Missouri—Rb-Sr glauconite dating at the Magmont Mine, Viburnum Trend: Economic Geology, v. 80, p. 739–753.

———1991, The significance of Rb-Sr glauconite ages, Bonneterre Formation, Missouri—Late Devonian-Early Mississippian brine migration in the midcontinent: Journal of Geology, v. 99, p. 468–481.

Sverjensky, D.A., 1981, The origin of a Mississippi valley-type deposit in the Viburnum Trend, southeast Missouri: Economic Geology, v. 76, p. 1848–1872.

Symons, D.T.A., and Sangster, D.F., 1991 Paleomagnetic age of the central Missouri barite deposits and its genetic significance: Economic Geology, v. 86, p. 1–12.

———1994, Paleomagnetic methods for dating the genesis of Mississippi Valley–type deposits, *in* Fontebote, L., and Boni, M., eds., Sediment hosted Zn-Pb ores: New York, Springer-Verlag, p. 42–58.

Taylor, M., Kesler, S.E., Cloke, P.L., and Kelly, W.C., 1983, Fluid inclusion evidence for mixing, Mascot-Jefferson City zinc district, Tennessee: Economic Geology, v. 78, p. 1425–1439.

Tobin, R.C., 1991, Diagenesis, thermal maturation and burial history of the Upper Cambrian Bonneterre dolomite, southeastern Missouri; an interpretation of thermal history from petrographic and fluid inclusion evidence: Organic Geochemistry, v. 17, no. 2, p. 143–151.

Thomas, W.A., 1976, Evolution of Ouachita-Appalachian continental margin: Journal of Geology, v. 84, p. 323–342.

Viele, G.W., 1979, Geological map and cross section, eastern Ouachita Mountains, Arkansas: Geological Society of America Map and Chart Series MC28F, scale 1:250,000, 1 sheet, 8 p.

Viets, J.G., and Leach, D.L., 1988, Ore deposition in the Viburnum Trend of southeast Missouri by two chemically distinct fluids: Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A39.

———1990, Genetic implications of regional and temporal trends in ore fluid geochemistry of Mississippi Valley-type deposits in the Ozark region: Economic Geology, v. 85, p. 842–861.

Voss, R.L., and Hagni, R.D., 1985, The application of cathodoluminescent microstratigraphy for sparry dolomite from the Viburnum Trend, southeastern Missouri, *in* Hausen, D.M. and Kopp, O.C., eds., Mineralogy-applications to the minerals industry, Proceedings, Paul F. Kerr Memorial Symposium: New York, American Institute of Mining Engineers, p. 51–68.

Voss, R.L., Hagni, R.D., and Gregg, J.M., 1989, Sequential deposition of zoned dolomite and its relationship to sulfide mineral paragenesis in the Viburnum Trend, Southeast Missouri: Society of Economic Paleontologists and Mineralogists, Carbonates and Evaporites, v. 4, no. 2, p 195–209.

Wisniowiecki, M.J., Van der Voo, R., McCabe, C., and Kelly, W.C., 1983, A Pennsylvanian paleomagnetic pole from mineralized Late Cambrian Bonneterre Formation, southeast Missouri: Journal of Geophysical Research, v. 88, p. 6540–6548.

Zartman, R.E., 1977, Geochronology of some alkalic rock provinces in eastern and central United States: Annual Review of Earth and Planetary Science, v. 5, p. 257–286.

Ziegler, P.A., 1988, Evolution of the Arctic-North Atlantic and the western Tethys: American Association of Petroleum Geologists Memoir 43, 198 p.

Zimmerman, R.K., and Kesler, S.E., 1981, Fluid inclusion evidence for solution mixing, Sweetwater (Mississippi Valley–type) district, Tennessee: Economic Geology, v. 76, p. 134–142.

APPENDIX OF SUPPLEMENTAL DATA

Original depths were measured in feet; feet are thus given here for completeness and were not converted to meters (conversion factor to meters: feet (ft) × 0.3048=meters (m)). Leaders (---), no data.

Zone	Th(v)	Tm(ice)	Depth (ft)	Formation/ Group	Sec.	T.	R.
Sample ARK-DW; location Arkansas							
---	---	---	3,000	Knox/Arbuckle	14	12N	9E
---	---	---	3,300	Knox/Arbuckle	14	12N	9E
IV	147.4	---	3,540	Knox/Arbuckle	14	12N	9E
IV	210	-19.4	3,540	Knox/Arbuckle	14	12N	9E
IV	---	-11.1	3,540	Knox/Arbuckle	14	12N	9E
IV	143	-11.2	3,540	Knox/Arbuckle	14	12N	9E
---	---	---	3,660	Knox/Arbuckle	14	12N	9E
---	---	---	3,960	Knox/Arbuckle	14	12N	9E
---	---	---	4,140	Knox/Arbuckle	14	12N	9E
---	---	---	4,820	Knox/Arbuckle	14	12N	9E
---	---	---	5,040	Knox/Arbuckle	14	12N	9E
IV	---	---	5,220	Knox/Arbuckle	14	12N	9E
---	---	---	5,400	Knox/Arbuckle	14	12N	9E
---	---	---	5,460	Knox/Arbuckle	14	12N	9E
---	---	---	5,520	Knox/Arbuckle	14	12N	9E
---	---	---	5,760	Knox/Arbuckle	14	12N	9E
IV	---	---	6,180	Knox/Arbuckle	14	12N	9E
IV	---	---	6,480	Knox/Arbuckle	14	12N	9E
IV	---	---	6,600	Knox/Arbuckle	14	12N	9E
---	---	---	6,840	Knox/Arbuckle	14	12N	9E
IV	---	---	7,020	Knox/Arbuckle	14	12N	9E
---	---	---	7,140	Knox/Arbuckle	14	12N	9E
IV	187	-7.9	7,680	Knox/Arbuckle	14	12N	9E
IV	---	-7.3	7,680	Knox/Arbuckle	14	12N	9E
---	---	---	7,980	Knox/Arbuckle	14	12N	9E
---	---	---	8,520	Knox/Arbuckle	14	12N	9E
---	---	---	8,640	Knox/Arbuckle	14	12N	9E
---	---	---	9,180	Knox/Arbuckle	14	12N	9E
IV	137.9	-4.9	9,240	Knox/Arbuckle	14	12N	9E
IV	137.2	---	9,240	Knox/Arbuckle	14	12N	9E
IV	178.8	---	9,240	Knox/Arbuckle	14	12N	9E
IV	173.9	---	9,240	Knox/Arbuckle	14	12N	9E
IV	176.7	---	9,240	Knox/Arbuckle	14	12N	9E

IV	176.7	---	9,240	Knox/Arbuckle	14	12N	9E
IV	180.8	---	9,240	Knox/Arbuckle	14	12N	9E
IV	192	---	9,240	Knox/Arbuckle	14	12N	9E
---	174	---	9,420	Knox/Arbuckle	14	12N	9E
---	194.2	-22.8	9,420	Knox/Arbuckle	14	12N	9E
---	174	---	9,420	Knox/Arbuckle	14	12N	9E
---	174	---	9,420	Knox/Arbuckle	14	12N	9E
---	180.5	---	9,420	Knox/Arbuckle	14	12N	9E
IV	178	-21.7	9,540	Knox/Arbuckle	14	12N	9E
IV	165	---	9,540	Knox/Arbuckle	14	12N	9E
IV	201	-21.6	9,540	Knox/Arbuckle	14	12N	9E
IV	---	-19.7	9,540	Knox/Arbuckle	14	12N	9E
IV	142	---	9,540	Knox/Arbuckle	14	12N	9E
IV	178	---	9,540	Knox/Arbuckle	14	12N	9E
IV	179	---	9,540	Knox/Arbuckle	14	12N	9E
IV	187.8	---	9,540	Knox/Arbuckle	14	12N	9E
IV	198.5	---	9,540	Knox/Arbuckle	14	12N	9E
IV	157.5	-21.2	9,540	Knox/Arbuckle	14	12N	9E
IV	---	-20.6	9,540	Knox/Arbuckle	14	12N	9E
IV	157.5	---	9,540	Knox/Arbuckle	14	12N	9E
IV	186	---	9,540	Knox/Arbuckle	14	12N	9E
IV	---	---	9,600	Knox/Arbuckle	14	12N	9E
IV	---	---	9,780	Knox/Arbuckle	14	12N	9E
IV	---	---	10,140	Knox/Arbuckle	14	12N	9E
IV	---	---	10,380	Knox/Arbuckle	14	12N	9E
IV	---	---	10,560	Knox/Arbuckle	14	12N	9E
---	---	---	10,680	Elvins Group	14	12N	9E
IV	---	---	11,040	Elvins Group	14	12N	9E
IV	---	---	11,340	Elvins Group	14	12N	9E
III	256	-18.5	11,880	Bonneterre	14	12N	9E
III	274.9	-17.9	11,880	Bonneterre	14	12N	9E
III	250.7	-17.7	11,880	Bonneterre	14	12N	9E
III	263.3	---	11,880	Bonneterre	14	12N	9E
III	---	-17	11,880	Bonneterre	14	12N	9E
III	169.7	---	11,880	Bonneterre	14	12N	9E
III	193	---	11,880	Bonneterre	14	12N	9E
III	193	---	11,880	Bonneterre	14	12N	9E
III	206.5	---	11,880	Bonneterre	14	12N	9E
III	221.8	---	11,880	Bonneterre	14	12N	9E
III	227.5	---	11,880	Bonneterre	14	12N	9E
III	230.2	---	11,880	Bonneterre	14	12N	9E
III	238.2	---	11,880	Bonneterre	14	12N	9E
III	243.4	---	11,880	Bonneterre	14	12N	9E

III	247	---	11,880	Bonneterre	14	12N	9E
III	247.4	---	11,880	Bonneterre	14	12N	9E
III	---	-22.1	11,880	Bonneterre	14	12N	9E
III	277	-15.6	11,880	Bonneterre	14	12N	9E
III	250	---	11,880	Bonneterre	14	12N	9E
III	255.5	-15.4	11,880	Bonneterre	14	12N	9E
III	247.6	-11.4	11,880	Bonneterre	14	12N	9E
III	---	-12.3	11,880	Bonneterre	14	12N	9E
III	197	-15.2	11,880	Bonneterre	14	12N	9E
III	152	---	11,880	Bonneterre	14	12N	9E
III	194	---	11,880	Bonneterre	14	12N	9E
III	250	-15.9	11,880	Bonneterre	14	12N	9E
III	255	---	11,880	Bonneterre	14	12N	9E
III	194.5	-23	11,880	Bonneterre	14	12N	9E
III	220.7	---	11,880	Bonneterre	14	12N	9E
III	188.8	---	11,880	Bonneterre	14	12N	9E
III	184.4	---	11,880	Bonneterre	14	12N	9E
III	185.3	---	11,880	Bonneterre	14	12N	9E
III	187.2	---	11,880	Bonneterre	14	12N	9E
III	189.8	---	11,880	Bonneterre	14	12N	9E
III	165.4	-25.9	11,880	Bonneterre	14	12N	9E
III	168.7	-29.5	11,880	Bonneterre	14	12N	9E
III	---	-28	11,880	Bonneterre	14	12N	9E
III	183.6	---	11,880	Bonneterre	14	12N	9E
III	184	---	11,880	Bonneterre	14	12N	9E
III	195.4	---	11,880	Bonneterre	14	12N	9E
III	245	-16.1	12,000	Bonneterre	14	12N	9E
III	150	**-13.7**	**12,000**	**Bonneterre**	**14**	**12N**	**9E**
III	**---**	**-13.9**	**12,000**	**Bonneterre**	**14**	**12N**	**9E**
III	---	-16.1	12,000	Bonneterre	14	12N	9E
III	242.2	---	12,000	Bonneterre	14	12N	9E
III	263	-14.9	12,000	Bonneterre	14	12N	9E
III	247.5	-15.5	12,000	Bonneterre	14	12N	9E
III	260	---	12,000	Bonneterre	14	12N	9E
III	---	-18.8	12,000	Bonneterre	14	12N	9E
III	229.7	---	12,000	Bonneterre	14	12N	9E
III	263	---	12,000	Bonneterre	14	12N	9E
III	259	---	12,000	Bonneterre	14	12N	9E
III	260.5	-9.9	12,000	Bonneterre	14	12N	9E
III	259	---	12,000	Bonneterre	14	12N	9E
III	258.4	-6	12,000	Bonneterre	14	12N	9E
III	259	---	12,000	Bonneterre	14	12N	9E
III	258.4	-6	12,000	Bonneterre	14	12N	9E

III	229.6	---	12,000	Bonneterre	14	12N	9E
III	239.9	-10.1	12,000	Bonneterre	14	12N	9E
IV	---	---	12,180	Bonneterre	14	12N	9E
Sample NMTW; location Missouri							
IV	129	-23	2,055	Bonneterre (?)	32	21N	14E
IV	136	-20.8	2,055	Bonneterre (?)	32	21N	14E
IV	138	-17.2	2,055	Bonneterre (?)	32	21N	14E
IV	176	-18	2,055	Bonneterre (?)	32	21N	14E
IV	207.5	---	2,055	Bonneterre (?)	32	21N	14E
IV	183.2	---	2,055	Bonneterre (?)	32	21N	14E
IV	213	---	2,055	Bonneterre (?)	32	21N	14E
IV	216.5	---	2,055	Bonneterre (?)	32	21N	14E
IV	---	-15.3	2,055	Bonneterre (?)	32	21N	14E
IV	206	---	2,055	Bonneterre (?)	32	21N	14E
IV	207	---	2,055	Bonneterre (?)	32	21N	14E
IV	---	-18.9	2,055	Bonneterre (?)	32	21N	14E
IV	147.1	-17.1	2,055	Bonneterre (?)	32	21N	14E
IV	---	-17.2	2,055	Bonneterre (?)	32	21N	14E
IV	191	---	2,055	Bonneterre (?)	32	21N	14E
IV	218.5	---	2,055	Bonneterre (?)	32	21N	14E
IV	236.6	---	2,055	Bonneterre (?)	32	21N	14E
IV	232.2	---	2,055	Bonneterre (?)	32	21N	14E
IV	205.9	-15.1	2,055	Bonneterre (?)	32	21N	14E
IV	---	-18.4	2,055	Bonneterre (?)	32	21N	14E
IV	227	-18.1	2,055	Bonneterre (?)	32	21N	14E
IV	---	-17.2	2,055	Bonneterre (?)	32	21N	14E
IV	---	-24.3	2,055	Bonneterre (?)	32	21N	14E
IV	248.5	-15.9	2,055	Bonneterre (?)	32	21N	14E
IV	220.5	-15.3	2,055	Bonneterre (?)	32	21N	14E
IV	234.5	---	2,055	Bonneterre (?)	32	21N	14E
IV	227.5	---	2,055	Bonneterre (?)	32	21N	14E
IV	128.1	-25	2,055	Bonneterre (?)	32	21N	14E
IV	159.6	---	2,055	Bonneterre (?)	32	21N	14E
IV	160	-24.7	2,055	Bonneterre (?)	32	21N	14E
IV	172.5	---	2,055	Bonneterre (?)	32	21N	14E
IV	164	---	2,300	Bonneterre (?)	32	21N	14E
IV	151	---	2,300	Bonneterre (?)	32	21N	14E
IV	218	-20.4	2,300	Bonneterre (?)	32	21N	14E
IV	175	---	2,300	Bonneterre (?)	32	21N	14E
IV	169.4	---	2,300	Bonneterre (?)	32	21N	14E
IV	163	---	2,300	Bonneterre (?)	32	21N	14E
IV	169	---	2,300	Bonneterre (?)	32	21N	14E

IV	200.7	-21.8	2,300	Bonneterre (?)	32	21N	14E
IV	197.2	---	2,300	Bonneterre (?)	32	21N	14E
IV	219.3	---	2,300	Bonneterre (?)	32	21N	14E
IV	224	---	2,300	Bonneterre (?)	32	21N	14E
IV	225	---	2,300	Bonneterre (?)	32	21N	14E

Sample JR4-18-89; location Imboden, Ark.

IV	---	---	100	Powell	2	17N	2W
IV	101.2	-16.6	100	Powell	2	17N	2W
IV	113.2	-18.9	100	Powell	2	17N	2W
IV	131.5	---	100	Powell	2	17N	2W
IV	129.5	-21.2	100	Powell	2	17N	2W
IV	117	-21	100	Powell	2	17N	2W
IV	117	-18.6	100	Powell	2	17N	2W
IV	118	---	100	Powell	2	17N	2W
IV	127.1	---	100	Powell	2	17N	2W
IV	131.9	---	100	Powell	2	17N	2W
IV	---	-20.2	100	Powell	2	17N	2W
IV	126.6	---	100	Powell	2	17N	2W
IV	124.1	---	100	Powell	2	17N	2W
IV	---	-21.6	100	Powell	2	17N	2W
IV	166.5	-22.3	100	Powell	2	17N	2W
IV	107.8	-19.3	100	Powell	2	17N	2W
IV	112.5	-15.5	100	Powell	2	17N	2W
IV	110	-15.1	100	Powell	2	17N	2W
IV	113.5	-22.9	100	Powell	2	17N	2W
IV	115.5	-16.6	100	Powell	2	17N	2W
IV	115.5	-22.4	100	Powell	2	17N	2W
IV	124	-22.3	100	Powell	2	17N	2W
IV	123.5	---	100	Powell	2	17N	2W
IV	124	---	100	Powell	2	17N	2W
IV	---	---	100	Powell	2	17N	2W
IV	---	-17.1	100	Powell	2	17N	2W
---	---	-23.7	100	Powell	2	17N	2W
---	---	-23	100	Powell	2	17N	2W
---	---	-17.2	100	Powell	2	17N	2W
---	---	-19.2	100	Powell	2	17N	2W
---	128.7	-21.8	100	Powell	2	17N	2W
---	120	---	100	Powell	2	17N	2W
---	119.8	---	100	Powell	2	17N	2W
---	114.6	---	100	Powell	2	17N	2W
---	---	-16.1	100	Powell	2	17N	2W
---	133.6	-24	100	Powell	2	17N	2W

---	121.4	-16.4	100	Powell	2	17N	2W
---	142	-23.4	100	Powell	2	17N	2W
---	112.5	---	100	Powell	2	17N	2W
---	112.5	---	100	Powell	2	17N	2W
IV	---	---	100	Powell	2	17N	2W
IV	185	-21.3	100	Powell	2	17N	2W
IV	---	-21.5	100	Powell	2	17N	2W
IV	118.5	-21.2	100	Powell	2	17N	2W
IV	---	-20.5	100	Powell	2	17N	2W
IV	112.4	-17.6	100	Powell	2	17N	2W
IV	107.7	-20	100	Powell	2	17N	2W
IV	---	-20.3	100	Powell	2	17N	2W
IV	110.5	-16.8	100	Powell	2	17N	2W
IV	107.5	-21.2	100	Powell	2	17N	2W
IV	---	-24.4	100	Powell	2	17N	2W
IV	---	-21.3	100	Powell	2	17N	2W
IV	130.7	-22.5	100	Powell	2	17N	2W
IV	122.5	-22.3	100	Powell	2	17N	2W
IV	120	-16	100	Powell	2	17N	2W
IV	120	-19.9	100	Powell	2	17N	2W
IV	113	-16	100	Powell	2	17N	2W
IV	124	-18.1	100	Powell	2	17N	2W
IV	144	-22.2	100	Powell	2	17N	2W
IV	151	-22.1	100	Powell	2	17N	2W
IV	---	-19.9	100	Powell	2	17N	2W
IV	---	-17.1	100	Powell	2	17N	2W
IV	121	---	100	Powell	2	17N	2W
IV	---	---	100	Powell	2	17N	2W
IV	185	-21	100	Powell	2	17N	2W
IV	---	-21.3	100	Powell	2	17N	2W
IV	114.4	---	100	Powell	2	17N	2W
IV	135.8	-21.1	100	Powell	2	17N	2W
IV	120.5	-18.3	100	Powell	2	17N	2W
IV	110.9	-21.6	100	Powell	2	17N	2W
IV	134	-22	100	Powell	2	17N	2W
IV	131.2	-22.7	100	Powell	2	17N	2W
IV	114.6	---	100	Powell	2	17N	2W
IV	112.3	---	100	Powell	2	17N	2W
IV	113	-23	100	Powell	2	17N	2W

Sample JR4-19-89; location Imboden, Ark.

IV	---	---	100	Powell		17N	2W

Sample JR5-22-89; location Imboden, Ark.							
IV	---	---	100	Powell	2	17N	2W
IV	---	---	100	Powell	2	17N	2W
IV	137.3	22.4	100	Powell	2	17N	2W
IV	126.8	21.5	100	Powell	2	17N	2W
IV	---	---	100	Powell	2	17N	2W
IV	135.5	-22.6	100	Powell	2	17N	2W
IV	---	-22.6	100	Powell	2	17N	2W
IV	126.3	-22.1	100	Powell	2	17N	2W
IV	126.3	-21.9	100	Powell	2	17N	2W
IV	113.2	-20.4	100	Powell	2	17N	2W
Sample PB-7; location Missouri							
IV	132.7	-23.1	1,137	Derby/Doe Run	3	24N	5E
III	143.4	-17.1	1,659	Derby/Doe Run	3	24N	5E
III	---	-23.5	1,659	Derby/Doe Run	3	24N	5E
IV	---	-24.2	1,659	Derby/Doe Run	3	24N	5E
III	103.4	-24.9	1,659	Derby/Doe Run	3	24N	5E
III	---	-20.9	1,659	Derby/Doe Run	3	24N	5E
III	97.3	-24.2	1,659	Derby/Doe Run	3	24N	5E
III	104.2	-22.3	1,659	Derby/Doe Run	3	24N	5E
IV	---	-19.8	1,659	Derby/Doe Run	3	24N	5E
---	109.7	---	1,659	Derby/Doe Run	3	24N	5E
IV	113.5	-18.3	1,678	Derby/Doe Run	3	24N	5E
III or IV	-9.7	---	1,678	Derby/Doe Run	3	24N	5E
I	137.7	-18.1	1,678	Derby/Doe Run	3	24N	5E
IV	148.8	---	1,678	Derby/Doe Run	3	24N	5E
IV	139.2	---	1,678	Derby/Doe Run	3	24N	5E
III		-20.5	1,678	Derby/Doe Run	3	24N	5E
III or IV	-11.3	---	1,678	Derby/Doe Run	3	24N	5E
I	143.3	---	1,678	Derby/Doe Run	3	24N	5E
---	---	---	2,190	Bonneterre	3	24N	5E
IV	---	-22.3	2,202	Bonneterre	3	24N	5E
IV	127.5	-23.5	2,202	Bonneterre	3	24N	5E
IV	---	-13	2,202	Bonneterre	3	24N	5E
IV	125	-10.5	2,202	Bonneterre	3	24N	5E
IV	120.1	-10.2	2,202	Bonneterre	3	24N	5E
Sample P-1; location Missouri							
---	115.6	-20.1	1,691	Post-Bonneterre	30	31N	10E
IV	102.3	-13.5	1,729	Post-Bonneterre	30	31N	10E

IV	---	-21.8	1,729	Post-Bonneterre	30	31N	10E
---	114	---	1,729	Post-Bonneterre	30	31N	10E
---	96.3	---	1,755	Post-Bonneterre	30	31N	10E
---	---	-17.9	1,755	Post-Bonneterre	30	31N	10E
---	119.8	---	1,755	Post-Bonneterre	30	31N	10E
---	---	-16.5	1,755	Post-Bonneterre	30	31N	10E
---	86.5	-21.9	1,755	Post-Bonneterre	30	31N	10E
---	125.7	---	1,755	Post-Bonneterre	30	31N	10E
---	---	-15	1,755	Post-Bonneterre	30	31N	10E
---	---	-14.4	1,755	Post-Bonneterre	30	31N	10E
---	---	-17.5	1,755	Post-Bonneterre	30	31N	10E
---	97.1	-21.1	1,755	Post-Bonneterre	30	31N	10E
---	58	-20.4	1,755	Post-Bonneterre	30	31N	10E
---	---	-12.7	1,755	Post-Bonneterre	30	31N	10E
---	71	-22.5	1,755	Post-Bonneterre	30	31N	10E
---	73.2	-22.5	1,755	Post-Bonneterre	30	31N	10E
---	---	-21.8	1,755	Post-Bonneterre	30	31N	10E
---	---	-18.2	1,755	Post-Bonneterre	30	31N	10E
---	100.7	-18.8	1,848	Post-Bonneterre	30	31N	10E
---	---	-6.8	1,848	Post-Bonneterre	30	31N	10E
---	106.2	-22.6	1,848	Post-Bonneterre	30	31N	10E
---	99	-19.6	1,848	Post-Bonneterre	30	31N	10E
---	93.6	-22.2	1,848	Post-Bonneterre	30	31N	10E
---	92.6	---	1,848	Post-Bonneterre	30	31N	10E
III	---	-20.8	2,074	Bonneterre	30	31N	10E
III	123.8	-20.5	2,074	Bonneterre	30	31N	10E
Sample GP-10; location Missouri							
III	---	-22.3	1,850	White Rock	---	---	---
IV	---	-15.3	1,850	White Rock	---	---	---
IV or III	---	-15.8	1,850	White Rock	---	---	---
---	126.2	-19.6	2,237	Basinal limestone	---	---	---
---	---	-11.3	2,237	Basinal limestone	---	---	---
---	---	-12.2	2,237	Basinal limestone	---	---	---
---	---	---	2,384	Basinal limestone	---	---	---
Sample PBW-3; location Missouri							
---	115.5	-1.5	1,710	Derby(?)	---	---	---
---	114.3	-0.3	1,710	Derby(?)	---	---	---
---	99.8	---	1,710	Derby(?)	---	---	---
---	---	-12.3	1,710	Derby(?)	---	---	---
---	96.3	---	1,710	Derby(?)	---	---	---

---	---	---	1,821	Davis(?)	---	---	---
---	---	---	2,223	Davis(?)	---	---	---
---	---	---	2,279	Davis(?)	---	---	---
---	110	-22.2	2,284	Davis(?)	---	---	---
---	110	-22.2	2,284	Davis(?)	---	---	---
---	123	-22.6	2,284	Davis(?)	---	---	---

Sample DP-4; location Tennessee

IV	---	-19.2	5,192	Knox	15	6S	19E
IV	---	-18.4	5,192	Knox	15	6S	19E
IV	---	-20.1	5,192	Knox	15	6S	19E
IV	109.3	---	5,648	Conasauga	15	6S	19E
IV	---	-21.5	5,648	Conasauga	15	6S	19E
IV	119.8	---	5,648	Conasauga	15	6S	19E
III	---	-19.2	5,648	Conasauga	15	6S	19E
IV	101.8	-14.5	5,648	Conasauga	15	6S	19E
III	---	-19.6	5,648	Conasauga	15	6S	19E
IV	118.7	---	5,648	Conasauga	15	6S	19E
III	114.4	---	5,648	Conasauga	15	6S	19E
IV	---	-15.1	5,661	Conasauga	15	6S	19E
IV	---	-17.7	5,661	Conasauga	15	6S	19E
IV	---	-15.6	5,661	Conasauga	15	6S	19E
IV	115.8	-16.2	5,661	Conasauga	15	6S	19E
IV	114.3	-22.9	5,661	Conasauga	15	6S	19E
IV	---	-21	5,661	Conasauga	15	6S	19E
I	---	-19.1	5,661	Conasauga	15	6S	19E
IV	106.6	---	5,661	Conasauga	15	6S	19E
III	111.3	-18.5	5,661	Conasauga	15	6S	19E
III	---	-20.1	5,661	Conasauga	15	6S	19E
III	---	-21.6	5,661	Conasauga	15	6S	19E
IV	---	-19	5,661	Conasauga	15	6S	19E
III	110.5	---	5,661	Conasauga	15	6S	19E
IV	121.2	---	5,661	Conasauga	15	6S	19E
IV	128.1	---	5,661	Conasauga	15	6S	19E
III	---	-18.9	5,661	Conasauga	15	6S	19E
III	106	-19.2	5,661	Conasauga	15	6S	19E
IV	136.7	---	5,661	Conasauga	15	6S	19E
IV	135.9	---	5,661	Conasauga	15	6S	19E
IV	143	-23.1	5,661	Conasauga	15	6S	19E
IV	111.6	---	5,661	Conasauga	15	6S	19E
I	105.9	---	5,661	Conasauga	15	6S	19E
IV	134.5	-22.4	5,663	Conasauga	15	6S	19E
IV	---	-17.5	5,663	Conasauga	15	6S	19E

III	---	-20	5,663	Conasauga	15	6S	19E
III	---	-16.9	5,663	Conasauga	15	6S	19E
III	---	-17.9	5,663	Conasauga	15	6S	19E
IV	---	-22.7	5,663	Conasauga	15	6S	19E
IV	114.9	-22.3	5,663	Conasauga	15	6S	19E
III or I	---	-21.9	5,663	Conasauga	15	6S	19E
III	---	-21.5	5,663	Conasauga	15	6S	19E
III	---	-21.6	5,663	Conasauga	15	6S	19E
III or IV	---	-21.6	5,663	Conasauga	15	6S	19E
III	129.8	---	5,663	Conasauga	15	6S	19E
III	---	-18.5	5,663	Conasauga	15	6S	19E
IV	119.2	-19.3	5,663	Conasauga	15	6S	19E
IV	109.2	---	5,663	Conasauga	15	6S	19E
IV	129.6	---	5,663	Conasauga	15	6S	19E
IV	134.8	---	5,663	Conasauga	15	6S	19E
Sample DP-2; location Tennessee							
---	---	---	4,420.7	Knox	14	6S	19E
---	---	---	4,996	Knox	14	6S	19E
---	---	---	6,087	Conasauga	14	6S	19E
---	---	---	6,377	Conasauga	14	6S	19E
---	---	---	6,380	Conasauga	14	6S	19E

Manuscript approved for publication March 3, 1997
Published in the Central Region, Denver, Colorado
Graphics and photocomposition by Gayle M. Dumonceaux
Edited by Lorna Carter
On-line version by Joan G. Nadeau

Availability of Publications of the U.S. Geological Survey

Order U.S. Geological Survey (USGS) publications from the offices listed below. Detailed ordering instructions, along with prices of the last offerings, are given in the current-year issues of the catalog "New Publications of the U.S. Geological Survey."

Books, Maps, and Other Publications

By Mail

Books, maps, and other publications are available by mail from—

USGS Information Services
Box 25286, Federal Center
Denver, CO 80225

Publications include Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, Fact Sheets, publications of general interest, single copies of permanent USGS catalogs, and topographic and thematic maps.

Over the Counter

Books, maps, and other publications of the U.S. Geological Survey are available over the counter at the following USGS Earth Science Information Centers (ESIC's), all of which are authorized agents of the Superintendent of Documents:

- Anchorage, Alaska–Rm. 101, 4230 University Dr.
- Denver, Colorado–Bldg. 810, Federal Center
- Menlo Park, California–Rm. 3128, Bldg. 3, 345 Middlefield Rd.
- Reston, Virginia–Rm. 1C402, USGS National Center, 12201 Sunrise Valley Dr.
- Salt Lake City, Utah–2222 West, 2300 South (books and maps available for inspection only)
- Spokane, Washington–Rm. 135, U.S. Post Office Building, 904 West Riverside Ave.
- Washington, D.C.–Rm. 2650, Main Interior Bldg., 18th and C Sts., NW.

Maps only may be purchased over the counter at the following USGS office:

- Rolla, Missouri–1400 Independence Rd.

Electronically

Some USGS publications, including the catalog "New Publications of the U.S. Geological Survey" are also available electronically on the USGS's World Wide Web home page at **http://www.usgs.gov**

Preliminary Determination of Epicenters

Subscriptions to the periodical "Preliminary Determination of Epicenters" can be obtained only from the Superintendent of Documents. Check or money order must be payable to the Superintendent of Documents. Order by mail from—

Superintendent of Documents
Government Printing Office
Washington, DC 20402

Information Periodicals

Many Information Periodicals products are available through the systems or formats listed below:

Printed Products

Printed copies of the Minerals Yearbook and the Mineral Commodity Summaries can be ordered from the Superintendent of Documents, Government Printing Office (address above). Printed copies of Metal Industry Indicators and Mineral Industry Surveys can be ordered from the Center for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh Research Center, P.O. Box 18070, Pittsburgh, PA 15236–0070.

Mines FaxBack: Return fax service

1. Use the touch-tone handset attached to your fax machine's telephone jack. (ISDN [digital] telephones cannot be used with fax machines.)
2. Dial (703) 648–4999.
3. Listen to the menu options and punch in the number of your selection, using the touch-tone telephone.
4. After completing your selection, press the start button on your fax machine.

CD-ROM

A disc containing chapters of the Minerals Yearbook (1993–95), the Mineral Commodity Summaries (1995–97), a statistical compendium (1970–90), and other publications is updated three times a year and sold by the Superintendent of Documents, Government Printing Office (address above).

World Wide Web

Minerals information is available electronically at **http://minerals.er.usgs.gov/minerals/**

Subscription to the catalog "New Publications of the U.S. Geological Survey"

Those wishing to be placed on a free subscription list for the catalog "New Publications of the U.S. Geological Survey" should write to—

U.S. Geological Survey
903 National Center
Reston, VA 20192

Selected Series of U.S. Geological Survey Publications

Books and Other Publications

Professional Papers report scientific data and interpretations of lasting scientific interest that cover all facets of USGS investigations and research.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars are reports of programmatic or scientific information of an ephemeral nature; many present important scientific information of wide popular interest. Circulars are distributed at no cost to the public.

Fact Sheets communicate a wide variety of timely information on USGS programs, projects, and research. They commonly address issues of public interest. Fact Sheets generally are two or four pages long and are distributed at no cost to the public.

Reports in the **Digital Data Series (DDS)** distribute large amounts of data through digital media, including compact disc-read-only memory (CD-ROM). They are high-quality, interpretive publications designed as self-contained packages for viewing and interpreting data and typically contain data sets, software to view the data, and explanatory text.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are produced on request (unlike formal USGS publications) and are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports can consist of basic data, preliminary reports, and a wide range of scientific documents on USGS investigations. Open-File Reports are designed for fast release and are available for public consultation at depositories.

Maps

Geologic Quadrangle Maps (GQ's) are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps (GP's) are on topographic or planimetric bases at various scales. They show results of geophysical investigations using gravity, magnetic, seismic, or radioactivity surveys, which provide data on subsurface structures that are of economic or geologic significance.

Miscellaneous Investigations Series Maps or **Geologic Investigations Series (I's)** are on planimetric or topographic bases at various scales; they present a wide variety of format and subject matter. The series also incudes 7.5-minute quadrangle photogeologic maps on planimetric bases and planetary maps.

Information Periodicals

Metal Industry Indicators (MII's) is a free monthly newsletter that analyzes and forecasts the economic health of five metal industries with composite leading and coincident indexes: primary metals, steel, copper, primary and secondary aluminum, and aluminum mill products.

Mineral Industry Surveys (MIS's) are free periodic statistical and economic reports designed to provide timely statistical data on production, distribution, stocks, and consumption of significant mineral commodities. The surveys are issued monthly, quarterly, annually, or at other regular intervals, depending on the need for current data. The MIS's are published by commodity as well as by State. A series of international MIS's is also available.

Published on an annual basis, **Mineral Commodity Summaries** is the earliest Government publication to furnish estimates covering nonfuel mineral industry data. Data sheets contain information on the domestic industry structure, Government programs, tariffs, and 5-year salient statistics for more than 90 individual minerals and materials.

The Minerals Yearbook discusses the performance of the worldwide minerals and materials industry during a calendar year, and it provides background information to assist in interpreting that performance. The Minerals Yearbook consists of three volumes. Volume I, Metals and Minerals, contains chapters about virtually all metallic and industrial mineral commodities important to the U.S. economy. Volume II, Area Reports: Domestic, contains a chapter on the minerals industry of each of the 50 States and Puerto Rico and the Administered Islands. Volume III, Area Reports: International, is published as four separate reports. These reports collectively contain the latest available mineral data on more than 190 foreign countries and discuss the importance of minerals to the economies of these nations and the United States.

Permanent Catalogs

"Publications of the U.S. Geological Survey, 1879–1961" and **"Publications of the U.S. Geological Survey, 1962–1970"** are available in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" is available in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Annual supplements for 1982, 1983, 1984, 1985, 1986, and subsequent years are available in paperback book form.